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A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries

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A B S T R A C T

Industrial processes account for one-third of global energy demand. The iron and steel, cement and refining sectors are particularly energy-intensive, together making up over 30% of total industrial energy consumption and producing millions of tonnes of CO_2 per year. The aim of this paper is to provide a comprehensive overview of the technologies for reducing emissions from industrial processes by collating information from a wide range of sources. The paper begins with a summary of energy consumption and emissions in the industrial sector. This is followed by a detailed description of process improvements in the three sectors mentioned above, as well as cross-cutting technologies that are relevant to many industries. Lastly, a discussion of the effectiveness of government policies to facilitate the adoption of those technologies is presented. Whilst there has been significant improvement in energy efficiency in recent years, cost-effective energy efficient options still remain. Key energy efficiency measures include upgrading process units to Best Practice, installing new electrical equipment such as pumps and even replacing the process completely. However, these are insufficient to achieve the deep carbon reductions required if we are to avoid dangerous climate change. The paper concludes with recommendations for action to achieve further decarbonisation.

Contents

Abbreviations: BAT, best available technology; BF, blast furnace; BOF, basic oxygen furnace; BP, best practise; CCA, climate change agreement; CCL, climate change levy; CCS, carbon capture and storage; CDM, clean development mechanism; CDQ, coke dry quenching; CDU, crude distillation unit; CHP, combined heat and power; DRI, direct reduced iron; EAF, electric arc furnace; ETS, emissions trading system; FCC, fluid catalytic cracker; ISIC, International Standard Industrial Classification; OHF, open hearth furnace; SMR, steam methane reforming; TGR, top gas recycling; TRT, top-pressure recovery turbine; VDU, vacuum distillation unit; VSD, variable speed drive

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1. Introduction

Industrial processes are highly energy intensive and currently account for one-third of global energy use [1]. Around 70% of this energy is supplied by fossil fuels. CO_2 emissions from industry make up 40% of total CO_2 emissions worldwide. If emissions from the industrial sector remain unchecked, total emissions are projected to increase by 74–91% by 2050 compared to 2007 [2]. The UN IPCC recommends that global CO_2 emissions should be reduced by at least 50% compared to 1990 levels by 2050, so as to confine the rise in global mean temperature to below 2 °C and to limit the possibility of dangerous climate change [3]. In order to realistically meet this target, the International Energy Agency (IEA) [2] recommends that by 2050, direct emissions from industry must be 24% lower than those in 2007. However, demand for manufactured goods is expected to be double or even greater by 2050 [4]. The majority of this growth will occur in developing or newly industrialised countries such as China, India, the Middle East and Africa to follow [2]. These countries are currently heavily dependent on fossil fuels, and coal in particular. Although newly built equipment in these countries is often state-of-the-art, a significant proportion of the capital stock is inefficient and outdated.

Since the 1990s, the energy consumption of industry per unit of value added in the IEA19 countries has decreased by ~1.3% per year on average (once adjusted for structural changes) [5]. This is less than in earlier decades. The 1970s and 1980s saw an average reduction in energy intensity of 2.8% per year. However, potential for improvement still remains, particularly in the non energy-intensive sectors. To date, energy costs for these industries have made up a smaller share of their costs, so they have had less incentive to improve their energy efficiency compared to energy-intensive industries. A headline conclusion of the World Energy Outlook 2012 [6] is that 'energy efficiency can keep the door to 2 °C open for just a bit longer'. The IEA suggests that if energy efficiency is made a priority (as in their Efficient World Scenario), savings in the industrial sector alone could amount to around 23 EJ (550 Mtoe), compared to their New Policy Scenario [6]. Total industrial energy use in the New Policy Scenario is 146 EJ (3497 Mtoe), hence energy efficiency can save around 15.7% of energy consumed.

This paper reviews the energy efficient and low carbon technologies for achieving energy and CO_2 savings in the industrial sector, focussing on three main sectors: (1) iron and steel, (2) cement and (3) refineries, as well as (4) crosscutting options (e.g. motor and steam systems and combined heat and power). The paper begins by defining the industrial sector and then gives an overview of past and present activity, energy consumption and CO_2 emissions from the industrial sector as well as the recent literature in this field (Section 2). The next Sections (3–5) look in detail at the energy efficiency technologies. These cover process-specific options in three sectors as well as crosscutting options. In each case, the overall production process is described and the sector is placed in context in terms of current production, energy consumption and emissions trends. The full range of energy efficiency technologies is discussed, including the energy savings potential and costs. In Section 9, the paper looks beyond energy efficiency and considers a range of other technologies for further decarbonising industry. Finally, in Section 10 the various policy mechanisms for encouraging the uptake of these technologies are introduced and discussed.

2. An overview of the industrial sector

2.1. Classification of industrial activity

The term 'industry' is often used very loosely in the context of both energy and CO_2 emissions. In some publications it is used to refer only to manufacturing and in others includes the power, mining and construction sectors. It is important to clarify exactly what is meant before making any assumptions. There are a

number of classification codes, of which the most widely recognised is the International Standard Industrial Classification system (ISIC), which is managed by the United Nations Statistics Division.

Fig. 1 shows a breakdown of the economic activity and the placement of industry and manufacturing activities within that. Economic activity is measured in terms of gross domestic product (GDP), which is approximately equal to the sum of the gross value added (GVA) from all resident producers. Where value added is the 'net output of a sector after adding up all outputs and subtracting intermediate inputs…without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources' [7]. This is usually divided into three economic sectors, namely: agriculture, industry and services. The agricultural sector refers to primary economic activities, i.e. those that are dependent on resources from the earth such as crop and animal production, forestry and fishing. Note that mining activities, however, are grouped with the industrial sector. The industrial sector comprises secondary economic activities, i.e. those that involve the processing of resources to produce new products. This includes mining, production of electricity, gas and water, construction and the manufacturing subsector. Lastly, the services sector is made up of a range of tertiary activities, which generate revenue from providing a service such as tourism, hospitality, healthcare and financial services.

Table 1 shows the main sources of high-level statistical information for the industrial sector and compares the information provided by these sources. The UNIDO database provides the value added from industry by sector and country. This can be compared to the World Bank database, which provides an aggregated number for industry and the manufacturing subsector. Both databases use ISIC revision 3 to classify their data. The IEA provides detailed energy and CO_2 statistics. The IEA has classified its data according to ISIC revision 4.

These statistics must be used with caution. In particular, there are a number of potential inconsistencies, which can arise from mismatching of ISIC classification codes when using data from different revision levels. In addition, these numbers are only as accurate as the countries that report them. The IEA states in their documentation that many countries are unable to supply a sectoral breakdown for all fuels. Where this is the case, 'non-specified (industry)' has been used. India is one example where this occurs. This could result in misrepresentation of the data, particularly when regions are aggregated.

It should be noted that in this paper, the term 'industry' refers exclusively to the manufacturing sub-sector, i.e. ISIC classification codes 15–37 (revision 3, 2012).

2.2. *Historical industrial energy consumption and emissions*

Economic growth and industrial activity are closely linked. The industrial revolution of the late 17th century sparked unprecedented economic growth. Over the last two centuries, there has been a dramatic increase in living standards and real income, predominantly in Europe, North America and the Pacific. More recently, China and other developing countries have entered a period of high growth. As these countries undergo the rapid expansion of the infrastructure required to underpin this growth, the demand for materials such as cement and steel has risen dramatically.

Total final energy use in the industrial sector in 2010 was around 100 EJ, as shown in Fig. 2 [1]. This is around 70% higher than in 1970. Much of the growth has occurred in the last decade, with energy consumption up from 80 EJ in 2000. A large proportion of the rise was due to growth in China, which grew by 16 EJ between 2000 and 2010. Fig. 3 shows the share of fuels, which

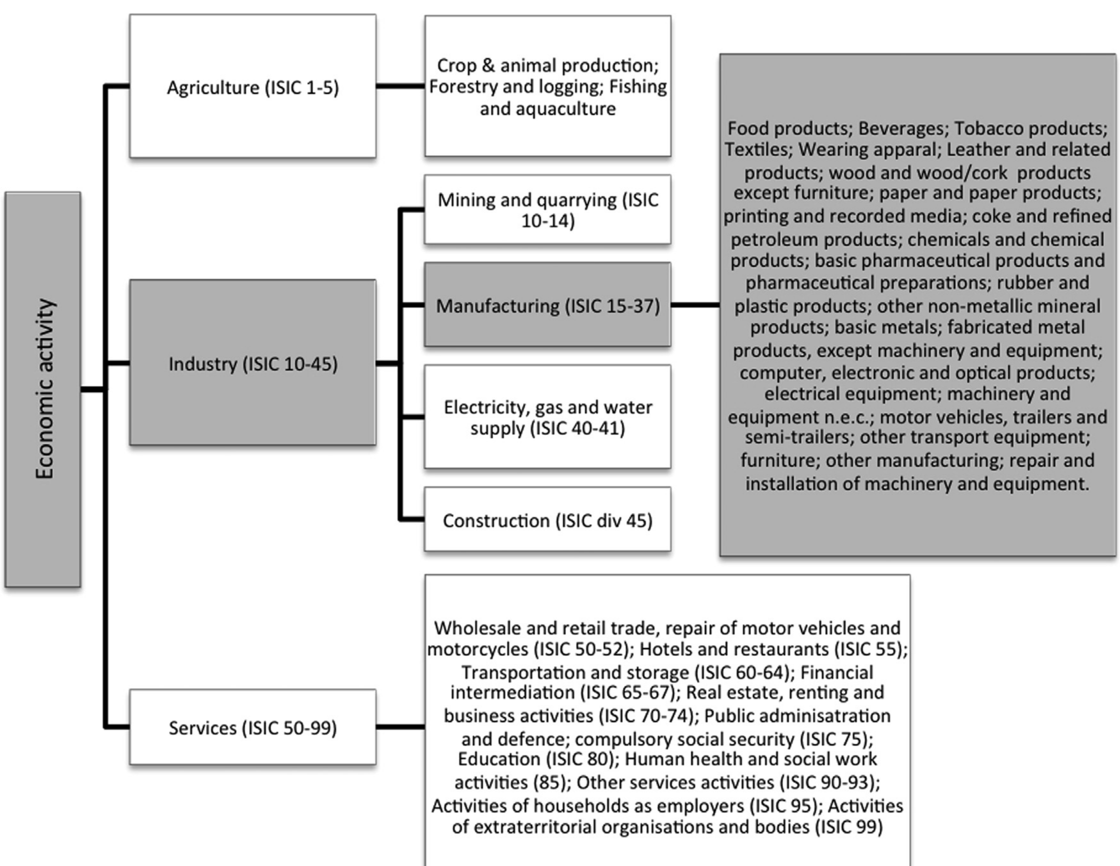


Fig. 1. Diagram showing the breakdown of economic activity and the placement of manufacturing activities within that based on ISIC revision 3 [8].

Table 1
Source of high-level key statistics and data for industry.

Key statistic	Database	Relevant information	Years	Countries	ISIC classification
Value added	UNIDO INDSTAT4 [8]	Value added by country, year and industrial sector Index numbers of industrial production	1985 to 2012	Divided two databases with countries A–M and N–Z. Most countries included. No regional groupings. No world total	3- and 4-digit level breakdown of ISIC Rev. 3. 151-3720
	UNIDO INDSTAT2 [8]	The value added by country, year and industrial sector Index numbers of industrial production	1963 to 2012	Most countries. No regional groupings. No world total	2-digit level breakdown of ISIC Rev. 3, Divisions 15-37
	World bank World Development Indicators [7]	A wide range of economic indicators, in particular: – Total Industry value added – Industry value added % of GDP – Manufacturing value added – Manufacturing value added % of GDP These are given by country/region and year	1960 to 2011	All countries as well as regional groupings. World total provided	No breakdown. Industry total only for ISIC rev. 3, Divisions 10-45 (Industry) and 15-37 (Manufacturing)
	EUROSTAT Structural Business Statistics [9]	Manufacturing value added for the EU27 by sector	2004 to 2007	Only EU27 aggregated total	2-digit level breakdown of ISIC Rev. 3, Divisions 15-37
Energy consumption	IEA World Energy Balances [1] (Note that the IEA World Energy Statistics contains the same information but in the original units)	Energy consumption (in TJ or ktoe) by fuel (including electricity), country, year and industrial sector	1960 to 2011 (not all regions have data for all years)	All countries as well as regional groupings. World total provided	2-digit level breakdown of ISIC Rev. 4, Divisions 07-32 (excl. 19: Coke and refined petroleum products). This includes construction, mining and quarrying
CO_2 emissions	IEA CO_2 emissions from fuel combustion [10]	CO_2 emissions from the combustion of fuels by country, year and fuel. Also includes from emissions from coke inputs to the blast furnace. Autoproducers that generate electricity and/or heat are allocated to 'Non-energy use industry/ transformation/energy' CO_2 from industrial processes refers to CO_2 from cement production	1960 to 2009	All countries as well as regional groupings. World total provided	2-digit level breakdown of ISIC Rev. 4, Divisions 07-32 (excl. 19: Coke and refined petroleum products). This includes construction, mining and quarrying. 3-digit level breakdown for the metals sector, which splits ferrous and non-ferrous metals production

made up this energy supply, with approximately 70% from fossil fuels. The options for replacing fossil fuels or switching to less carbon intensive fossil fuels are limited and these will likely remain the predominant source of energy in industry.

Industrial emissions include both direct emissions (emitted on site) and indirect emissions (emitted as a result of the generation of electricity at a separate power station). As shown in Fig. 4, currently, indirect emissions make up around 32% of total industrial CO_2 emissions [2]. Direct emissions can be further separated into (i) 'combustion emissions' i.e. those that arise from the combustion of fuels for heat used during various stages of the production process and (ii) 'process emissions' i.e. those which are the product of a chemical reaction, e.g. from the conversion of limestone ($CaCO_3$) into lime (CaO). The largest contributors to emissions are the production of iron & steel and cement [2]. These collectively contributed around 4.3 Gt, or 56%, of industrial CO_2 emissions in 2007. A further 17% was from chemicals and petrochemicals. This covers a wide range of refining processes and the production of organic and inorganic chemicals. Aluminium production and pulp and paper processes made up a further 4%. The remaining 23%, or 1.7 Gt of emissions, arose from a large number of smaller processes.

Indirect emissions can be addressed by the decarbonisation of the electricity sector. In addition, demand for electricity can be reduced through improved efficiency of various electrical appliances such as refrigerators and motor-driven equipment such as

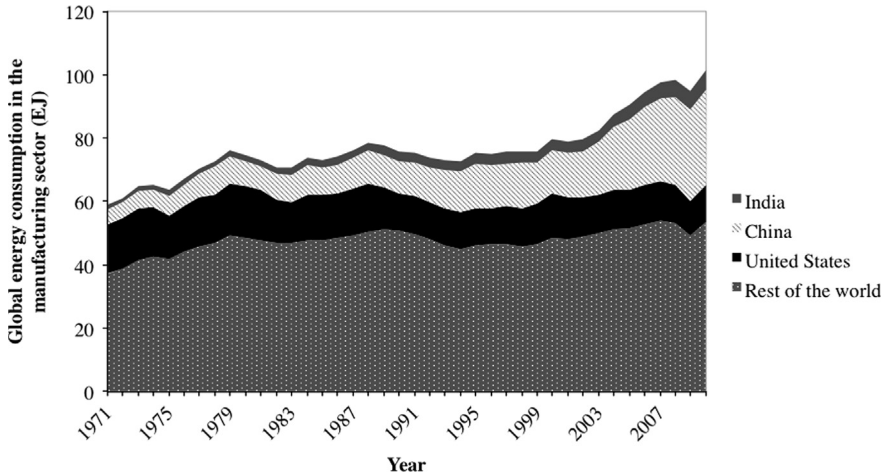


Fig. 2. Global energy consumption in the manufacturing sector (EJ). ISIC rev. 3, divisions 15–37 [1].

fans, compressors and pumps. In some cases, assuming a largely decarbonised power sector in the future, there is an argument for increasing the share of energy from electricity in order to decrease dependency on fossil fuels as an energy source. However, very careful lifecycle assessment must be done to ensure that this makes sense.

2.3. The literature landscape on industrial energy efficiency

A substantial amount of literature exists on this topic, spanning both academic journal papers and grey literature such as industry and government reports. A number of sources have attempted to pull this information together. The IEA's Energy Technology Perspectives gives an overview of energy efficiency technologies and issues as well as projections of future scenarios for industry. All three of the most recent editions (2008, 2010 and 2012) have a section on industry. Supporting these documents and going into greater technical detail, the IEA has also published two other reports focussing on industry: Tracking Industrial Energy Efficiency (2007) and Energy Technology Transitions for Industry (2009). The most recent World Energy Outlook (2012) has a special focus on energy efficiency with a dedicated section on the industrial sector.

The Lawrence Berkley National Laboratory (LBNL) has done extensive research in this field and has produced a considerable number of papers, describing energy efficiency technologies and their economics. Their research has a particular focus on iron and steel, cement, and crosscutting technologies such as steam and motor systems. Other authors have also focussed on these sectors: Gielen and Moriguchi have investigated the emissions reduction potential of the Japanese iron and steel sector using a linear programming model. The model includes very basic costing of some key abatement technologies. The IEA Clean Coal Centre has produced two comprehensive reviews of the iron and steel sector and cement sector [11,12]. Ozawa et al. [13] have analysed the energy and CO_2 emissions from the Mexican iron and steel sector using decomposition analysis to differentiate between intra-sectoral structural changes and efficiency improvements. They cite an LBNL paper by Worrell et al. [14] when referring to costs. There is limited literature available on the other industrial sectors.

Energy-technology models require comprehensive and reliable databases of available technologies and their associated costs in order to model potential decarbonisation pathways. For example, the ETSAP-TIMES model [15] has a high-level technology and cost detail in its database. The disadvantage of this is that it is not transparent and is not regularly updated.

The Institute for Industrial Productivity has put together the Industry Efficiency Technology Database. This database is available online and comprehensively covers the range of energy efficient technologies for iron and steel and cement as well as cross cutting technologies which can be applied to most industrial processes.

In the UK, focus on industrial energy efficiency has been increasing. In 2010 the UK's Committee on Climate Change commissioned the consultancy AEA Technology to study the abatement potential and costs of reducing CO_2 emissions in the UK industrial sector. This report [16] informed the mitigation potential, and costs, in the UK industrial sector to 2030.

Table 2 summarises the key resources covering energy efficient technologies in the industrial sector.

3. Objectives and scope

As has been shown in the previous section, there is a significant amount of literature on this topic, however it is spread out across a range of different sources including academic papers, grey literature and industry reports. The main aim of this review is to synthesise the literature across these sources. This paper provides a comprehensive overview of the subject including: description of production processes, details of the key technologies for improving energy efficiency, energy savings potential and costs. In order to ensure the comparability of costs, all costs have been translated to 2011 US$ for comparison using the IMF's exchange rates [24] and the U.S. Bureau of Labor Statistics' inflation rate [25]. Where the currency year was not given in the literature, it was assumed to be the year before publication. Additionally, energy savings are all reported.

This paper focuses on three industrial sectors, namely: iron and steel, cement and refineries. These three sectors together consume around 38% (43 EJ) of total final industrial energy as shown in Fig. 5. Whilst there is a significant amount of published literature on the iron and steel and cement sectors, the refineries sector is often overlooked despite its significant share of energy consumption. This paper shows that there are still untapped energy efficiency opportunities in the refineries sector. In addition, these three sectors are relatively homogenous, each having only one or two many production processes. By comparison, the chemicals sector is very heterogeneous and is made up of many different processes each producing a wide range of products. Each of these processes requires its own analysis to fully optimise the process. There are, however, a number of crosscutting technologies, which

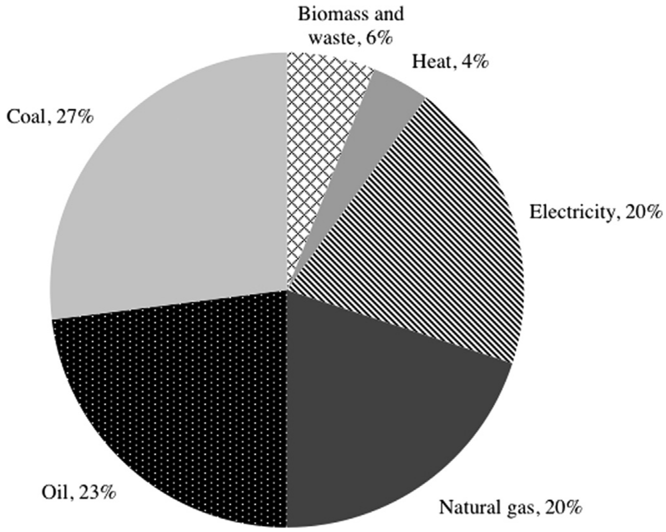


Fig. 3. Breakdown of the total final energy use in industry in 2007 by fuel. Total final energy consumption was 127 EJ, globally. IEA Energy Balance [1].

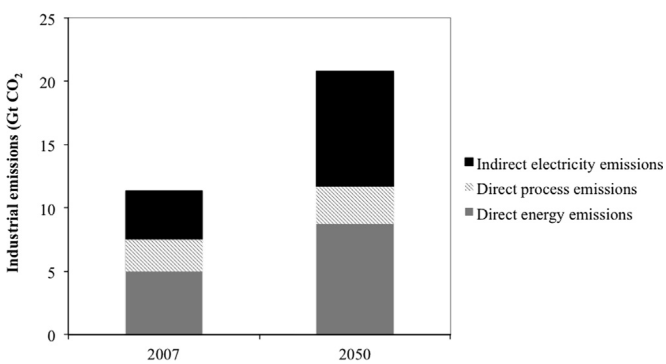


Fig. 4. CO_2 emissions from industry in 2007 and projected for 2050 (assuming business-as-usual), broken down by emissions type. Based on IEA data [2].

can be applied to common processes such as motors, steam and compressed air systems. These are also addressed in this paper.

4. Iron and steel

4.1. Description of the process

An overview of the routes of iron and steel production are shown in Fig. 6. Production can be grouped into two main routes: (1) primary steel production, where steel is produced from iron made from raw iron ore or (2) secondary steel production from recycled steel scrap [27].

The most common primary steel production route is the basic oxygen process. This is a two-stage process involving iron production in a blast furnace (BF) and steel production in a basic oxygen furnace (BOF)—sometimes referred to as basic oxygen steelmaking (BOS). In this process, the iron ore powder is first sintered at high temperature, producing porous agglomerates for feeding into the blast furnace. In the blast furnace, iron ore is converted to iron by reduction with CO (produced from the partial oxidation of coking coal) at temperatures of up to 1450 °C [27]. The resulting "pig iron" has a number of impurities (such as Mn, S and P) and a carbon content of 4.5 wt% [27]. The iron is then transferred to the basic oxygen furnace (BOF), where high purity oxygen at temperatures in excess of 1600 °C is used to remove carbon and other impurities from the pig iron, forming steel with a carbon content of $<0.05\%$. The BOF has largely replaced its precursor, the open hearth furnace (OHF), where pig iron is converted to steel by heating it in the presence of air. Both the BOF and OHF can be supplemented with scrap steel to produce new steel [27].

The main reducing agent in both the blast furnace (BF) and basic oxygen furnace (BOF) is coke. Coke is a highly energy-intensive fuel, which is produced from speciality coking coal (known as metallurgical coal) by heating it slowly in an oxygen-free environment.

In the secondary steel production process, recycled steel scrap is melted by applying high power electric arcs in an electric arc furnace (EAF). Steel scrap can be supplemented with an alternative to pig iron called direct reduced iron (DRI), also known as 'sponge iron'. DRI is produced by reducing iron ore in the presence of coal or natural gas. The direct reduction process operates at a lower temperature and, unlike in the blast furnace, the iron ore is not melted. The resulting iron is generally of higher purity than pig iron from the blast furnace process and is a suitable raw material for electric arc furnaces. The DRI process combined with EAF is an alternative primary steel production route to the BF-BOF process [27].

Traditionally, crude steel was first cast into ingots by pouring molten metal into moulds. These ingots were then further cut or shaped into the desired final product. Today, ingot casting has largely been replaced by continuous casting. Here, molten metal is continuously poured into the top of a long mould, the metal cools as it passes down the length of the mould and is cut to the desired size as it exits the other end. Continuous casting is normally followed directly by hot rolling in order to shape the metal into the final product [27].

4.2. Current status

Iron and steel are two of the most widely used materials in the world. Globally, almost 1500 Mt of crude steel were produced in 2011, with more than 45% being produced in China alone, making it the largest producer of crude steel in the world (Fig. 7). China's contribution to global steel production has risen rapidly in the last decade. In 2001, China's total steel production was 150 Mt, representing just 18% of global production.

Projections in the literature (Fig. 8) indicate that global steel production could reach between 2400 and 2850 Mt by 2050. The majority of this growth is expected to come from developing countries such as India and China and, in the latter years, African countries. However, there is a huge uncertainty in these projections. A literature survey of projected steel production in China is presented in Fig. 9. Here, projected production in 2050 ranges from less than 400 to 900 Mt. In recent years, growth Chinese steel production has been around 10% per annum, significantly higher than the average annual growth rate of 4% projected by the most recent study by the Lawrence Berkley National Laboratories (LBNL) [26] for the period of 2005 to 2030.

Fig. 10 shows the total global energy consumption of the iron and steel sector broken down by fuel since the 1970s. Total energy consumption in 2010 was 17.6 EJ. This is almost double the energy demand in the 1990, which was around 10 EJ. Coal and coal products supply around 60% of the energy consumed in the iron and steel sector. Global CO_2 emissions from the iron and steel sector were 2.3 Gt in 2007 [2].

4.3. Energy efficiency potential

In the iron and steel sector there are three key ways in which significant energy savings and hence also CO_2 emissions savings can be achieved. These are:

- switching to more efficient processing routes such as phasing out open hearth furnaces and increased use of scrap with electric arc furnaces;

Table 2
Key resources covering energy efficiency technologies in the industrial sector.

Study	Year	Region	Report type	Sectors	Discount rate	Details	Comment
McKinsey [17]	2009	Global	Consultancy report	Iron and steel, cement, chemicals and petrochemicals	4%	Development of Marginal Abatement Cost curves based on consultation with experts. Assumptions of cost and penetration are explicitly given in the appendix	
AAP Steelmaking Handbook [18]	2010	Asia-pacific	Review	Iron and steel	NA	Detailed descriptions of energy and CO_2 saving technologies, their costs, stage of development and level of deployment. Based on a wide range of literature. Costs are based on literature review and assumptions are not explicit	
Madlool et al. 2011 [19]	2011	Global	Review	Cement	NA	Comprehensive collection of energy saving measures and their associated fuel saving, electricity saving, costs and emissions reduction potential as presented in the literature	
Environmental Protection Agency [20]	2012	US	White paper	Iron and steel	NA	Detailed descriptions of the energy and CO_2 saving technologies for the iron and steel sector. Costs are largely drawn from an earlier paper published by Worrell et al. 1999. Here assumptions around fuels savings, electricity savings, annual operating cost, retrofit capital cost and the associated emissions reduction potential and payback time are made explicit	
Bloomberg NEF [21]	2009	EU	Research	Iron and steel, cement and lime, oil refineries, other industries	Not stated	Construction of a detailed MAC curve of the abatement potential in the industrial sector. Assumptions were based on literature review and interviews with industry specialists, plant manufacturers and industrial companies. Assumptions regarding change in energy intensity, change in carbon intensity, CAPEX, OPEX and penetration are made explicit	
Tsinghua 2008 [136]	2008	China		Cement	Not stated	This appears to be an original study documenting the fuel/electricity savings and carbon emissions reductions of different technologies as well as the penetration of these technologies, ultimately producing a MAC curve for the Chinese Cement sector	It is uncertain from where the data for this study was obtained. Cost sources are also not provided.
AEA [16]	2010	UK	Consultancy report	Iron and steel, refineries, chemicals, cement, food and drink, glass	Energy savings were discounted at 3.5%, Capex was discounted at 10%	A study of the abatement potential in key industrial sectors in the UK. Three scenarios of the penetration of key technologies were developed: technical potential, cost-effective potential and realistic potential. MAC curves for these scenarios were also developed	This was a study commissioned by the Committee on Climate Change
Wang et al. [22]	2009	China	Research	Iron and steel	Not given	Scenario analysis of future energy demand and emissions for the Chinese iron and steel sector using LEAP. Cost of the different scenarios was also calculated. This was based on assumptions around cost effectiveness, penetration and total emissions reduction potential of different technologies. These are given explicitly, however underlying assumptions such as CAPEX and OPEX are not	Costs are based on literature and interviews with experts, however specific sources were not provided
Energy Technology Perspectives [2]	2010	Global	Research	Industry as a whole	NA	Overview of the current status and future decarbonisation pathway for the global industrial sector. Projected emissions and energy consumption of industry in 2050 are presented for the baseline and BLUE map scenarios at both a low and high demand level	
Hasanbeigi et al. [23]	2010	Thailand	Research	Cement	10% (including sensitivity analysis)	Comprehensive list of technologies with details of the associated fuel/electricity savings, capital costs and penetration rates. These are used to create a Marginal Abatement Cost curve for the Thai cement industry. Detailed cost assumptions are provided in a separate study	LBNL study

- increased recovery of gases and heat integration from the blast furnace and basic oxygen furnace;
- adoption of efficient methods for casting and rolling of the final crude steel product

In all cases, energy savings and costs have been reported per tonne of crude steel. Data reported in the literature was scaled according to the reference plant described in [14].

4.3.1. Manufacturing route

Globally, almost 70% of steel was produced in basic oxygen furnaces (BOF) in 2010. Open-hearth furnaces (OHF) have been phased out over the past decade and today, less than 2% of steel produced worldwide is manufactured in OHFs [28]. The majority of these furnaces are in Russia, Ukraine and India. The remaining steel (29%) is produced in Electric Arc Furnaces (EAF). A number of countries produce steel entirely via the EAF route, including: Greece, Portugal, much of Eastern Europe, the Middle East, some of African and smaller Asian countries. In China, less than 10% of steel was produced in EAFs, the majority of production occurring in coal-intensive BF-BOF processes. Around 9% of global steel is produced from direct reduced iron (DRI). Most DRI (more than 90%) is natural gas-based, largely in the Middle East and South America. Coal-based DRI facilities exist largely in India [33].

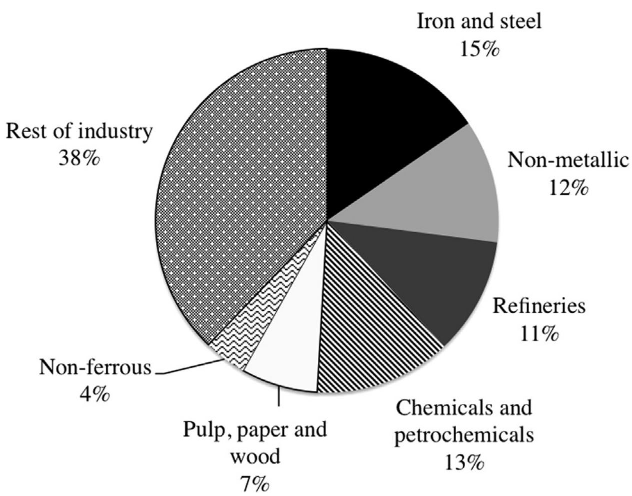


Fig. 5. Share of global industrial final energy consumption by sector in 2010. Total final energy consumption in 2010 was 114 EJ [1], excluding petroleum feedstocks.

Table 3 shows the energy intensity of the different steel manufacturing routes and their sub-units. Both best practice and laggard (i.e. most inefficient technologies still in operation. Indication of the worst-case scenario) technologies are shown. The open-hearth furnace (OHF) is the most inefficient processing route. It is estimated that completely replacing OHFs with basic oxygen furnaces (BOF) would save around 100 PJ per year (or 2% of total energy savings potential). The majority of steel is produced using the BF-BOF route. The Best Available Technology (BAT) for this production route has an energy efficiency of 19.8 GJ per tonne of crude steel.

The energy intensity of the scrap-EAF secondary steel production route is much lower than the BF-BOF route. Switching from BF-BOF to scrap-EAF can make significant energy savings (implications for the overall lifecycle emissions are discussed in the section on lifecycle and systems approach). The limiting factor is the supply of cheap electricity and scrap steel. Steel scrap comes from vehicles, machinery, packaging, white goods and buildings, which can take 10–100 years to be discarded and become available for scrap. As economies mature, the supply of scrap increases and the recycling rate can increase. According to 2007 statistics, for example, the rate of recycling of steel [34] in Germany was 91%.

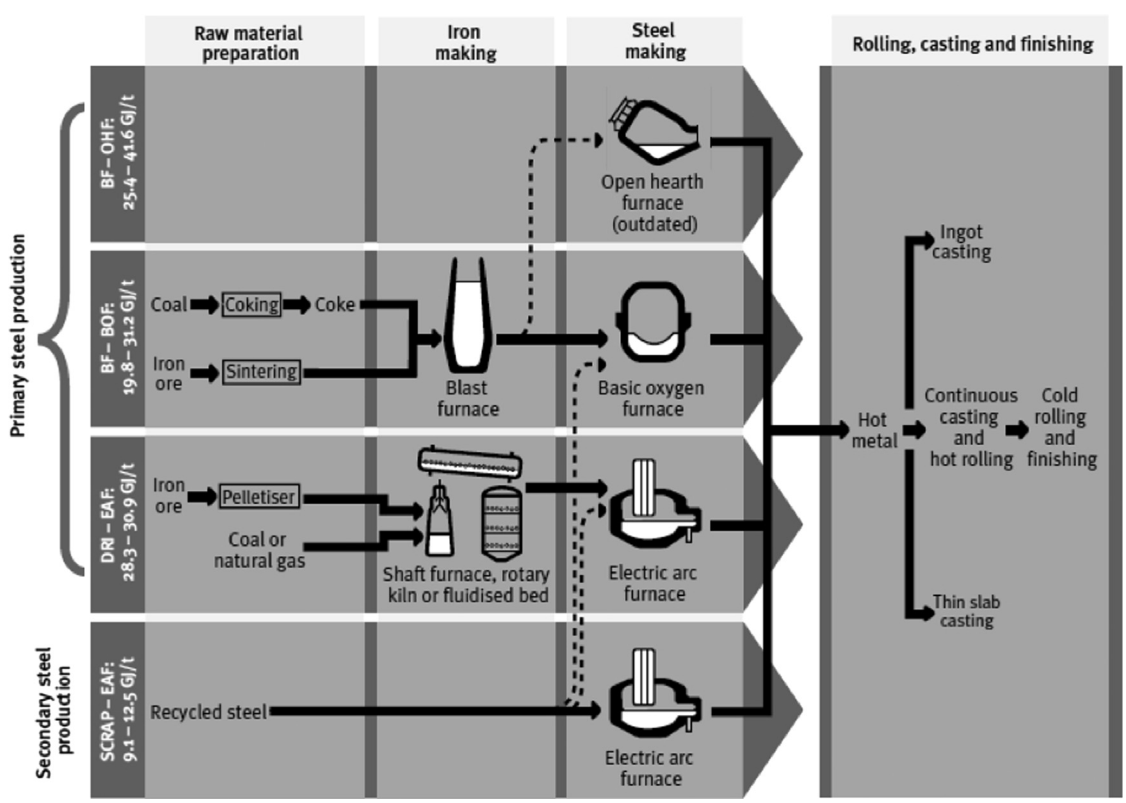


Fig. 6. Steel production routes and energy intensity per route (in units of GJ per tonne of crude steel produced) adapted from Worldsteel Energy Factsheet [137]. Steelmaking processes can vary from one facility to another and energy intensity varies depending on steel grade produced and technology used. Energy intensity values are based on CO_2 intensity values from Worldsteel 2007 data [28].

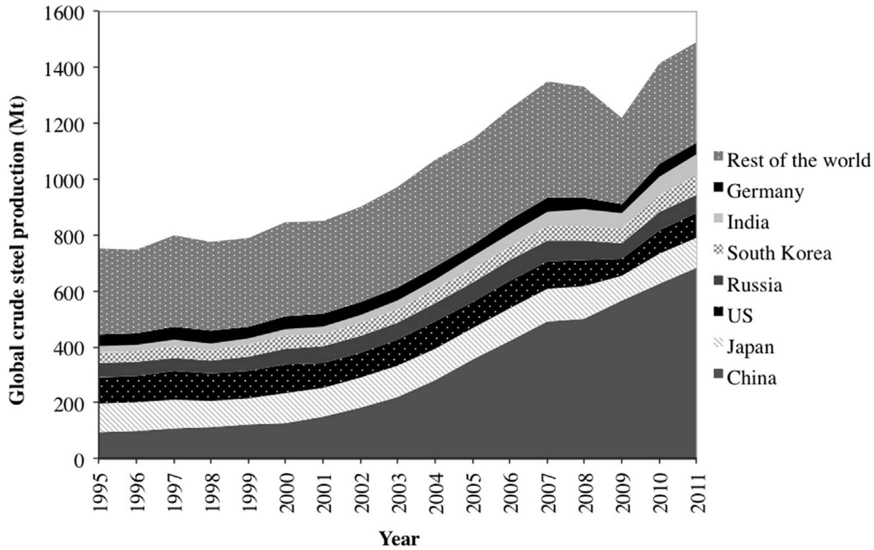


Fig. 7. Global crude steel production (Mt) between 1995 and 2011, showing contributions from top steel producing countries. Source: World Steel Statistical Archives [28].

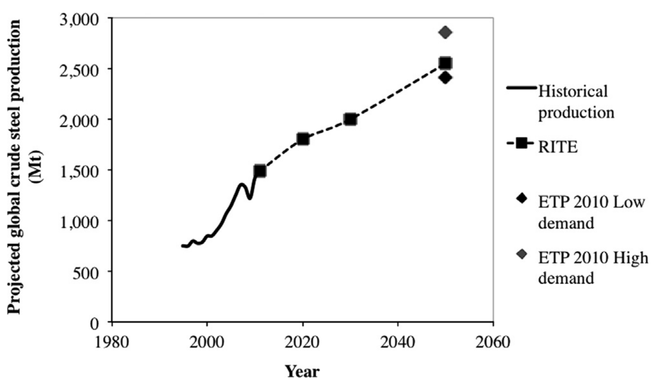


Fig. 8. Projected global crude steel production in 2050. Sources: Historical production [28], RITE [29] and ETP [2].

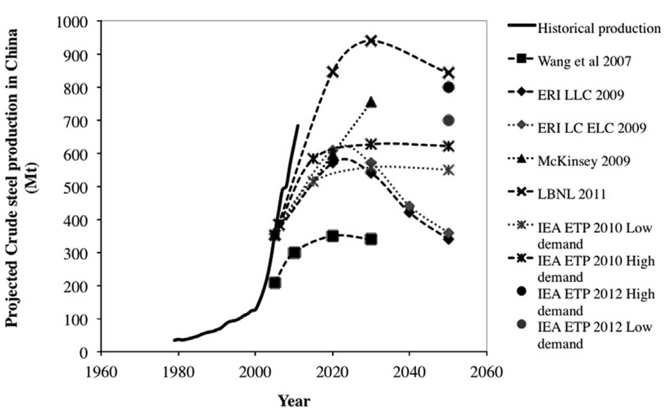


Fig. 9. Comparison of the projected crude steel production for China from a range of sources (Historical production [30], Wang et al. [22], ERI [31], McKinsey [17], LBNL [26], IEA ETP [2,32]).

4.3.2. Waste gas recovery and heat integration

The various processes on an iron and steel plant generate a number of sources of heat and high-calorific gases. Clever re-use and integration of these streams can significantly reduce the energy requirements for these processes. Much of the energy savings to date have focussed on individual process units on the plant and a 'plant-wide approach' is often not applied. This is highlighted in a Japanese study by Matsuda and colleagues [36], who have analysed the potential for heat integration on a large (8 Mt/yr) steel plant using pinch analysis. This study showed that although the steel plant was considered relatively advanced and energy efficient, significant further savings could be achieved by taking a system-wide view of the plant. There was potential for power generation of 21.1 MW and two combined heat and power (CHP) plants (6.2 and 12.3 MW). Table 4 summarises the key energy saving options from heat integration and waste heat recovery across the iron and steel plant.

A significant amount of waste heat can be recovered from the sinter plant. This is typically used to produce high-pressure steam for power generation. Both retrofit and new build is possible and energy savings range from between 0.25 and 0.55 GJ/t sinter [20]. Around 5 MJ_e/t sinter (1.4 kWh/t sinter) of electricity can be generated. Taking an even wider view, waste heat recovered from the sintering process can also be used for district heating. This has been demonstrated in Korea, where heat from sintering provided 800 TJ/yr, heating 5000 homes [37].

Coke ovens can be broadly classified into recovery ovens and non-recovery ovens. Recovery ovens are the more common type, with coke oven gases exiting the oven uncombusted. By comparison, in a non-recovery oven the gases are fully combusted in the oven, generating the heat for coking, and exit gases are sent to a waste heat recovery boiler, which generates steam for power generation. Coke oven gas from recovery ovens has a low calorific value, but it should not be wasted [38]. Coke oven gas can successfully be used as a fuel to replace natural gas in the coke oven or in furnaces and boilers [20]. Coke oven gas can also be used to supplement methane in methane reforming processes to produce syngas. Waste heat from the coke oven gas can be used to dry the coal prior to coking. This reduces the fuel consumption in the coke oven by 0.3 GJ/t coke and also improves the quality of the coke. However, installation of this equipment is very expensive resulting in a payback time of over 50 years [20]. Coke oven gas recovery depends on the location of coke manufacturing. In an integrated steel plant, typically 97% of coke oven gas is recovered. However, coke oven gas recovery is less common for coke ovens situated near mines as there are fewer uses for the gas; gas flaring is still the common practice here.

After coking, the coke needs to be cooled before exiting to prevent it oxidising in the presence of air. Traditionally this was

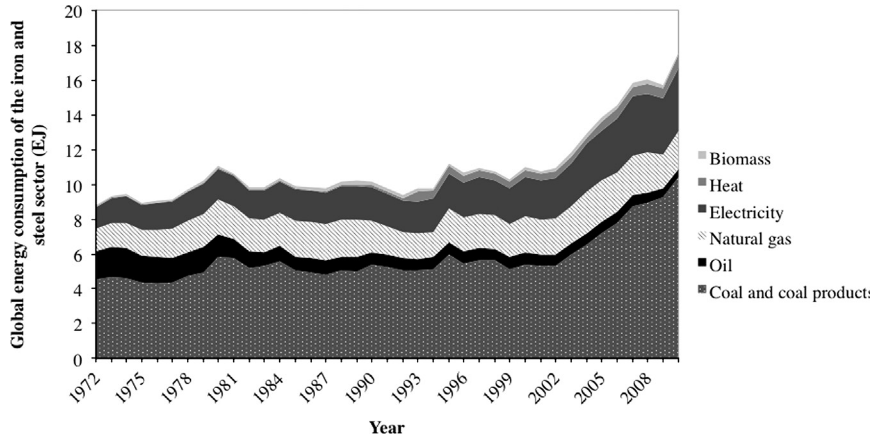


Fig. 10. Share of fuels consumed by the iron and steel sector between 1971 and 2010 [1].

Table 3
Final energy intensity values.
Sources: [33,35].

Unit operation	Best practice (GJ/t crude steel)	Laggard (GJ/t crude steel)
Materials preparation		
Coke production	0.84	6.7
Sintering	1.5	3.2
Iron production		
Blast furnace	11.6	18.6
Direct reduced iron	10.9	16.9
Steel production		
Basic oxygen furnace + refining	−0.45	2.2
Electric arc furnace	2.4	9.5
Smelt reduction	13	18
Post-processing		
Casting, rolling and finishing	0.6	8.6
Overall energy intensities of whole process route		
BF-BOF	14.1	39.3
DRI-EAF	15.4	38.2
Scrap-EAF	2.96	18.1
Smelt-BOF	13.1	20.8

Note: Full process routes include relevant materials preparation and post processing.

done by spraying the coke with water (wet quenching), but an alternative known as 'dry quenching' uses inert gas to recover sensible heat from the coke. Coke dry quenching (CDQ) is slowly replacing wet quenching in most countries, particularly in Japan (95% of plants) [33]. However, EU and the US are lagging behind; CDQ has not yet been applied to any coke plants in the US [20].

Blast furnace (BF) gas can be recirculated and used again in the furnace; the CO and H_2 generated are used as a fuel. By combining BF gas with coke oven gas to increase its calorific value, it can be used in a CHP plant to generate electricity. A large volume of gas at slightly elevated pressure exits the blast furnace. This pressure can be recovered from the gas exiting the blast furnace using a top-pressure recovery turbine (TRT) and used to generate electricity [20]. A number of major steel mills around the world have TRTs installed. Alternatively, blast furnace heat recuperation systems such as the hot blast stove and the BF gas preheating system can use heat from the BF to preheat the air entering the BF [18].

The development of BOF gas recovery has generated the largest savings in this process step, making the BOF unit a net energy generator. The air entering the furnace is controlled such that the CO is not fully converted to CO_2. High-pressure steam is generated from the sensible heat of the off-gas in a waste heat boiler. The exhaust gas is then cleaned and recovered for use as a fuel [18]. In China, BOF gas recovery has increased from 55% in 1995 to 89% in 2003.

In theory, heat can also be recovered from the blast furnace slag, although as yet there are no commercially operating recovery systems. A large amount of the heat from the BF slag is emitted as radiation. One method of recovering this radiation is using thermophotovoltaics (TPV). Here the radiation is absorbed by a photovoltaic diode cell and converted into electricity. This technology can also be applied to the slabs following casting, ladle metallurgy and panels on the roof and sides of the EAF [39].

Waste heat from the EAF can be used to preheat scrap, significantly reducing the power consumption of the EAF. A number of different systems have been developed including the Consteel tunnel-type preheater, Fuchs finger shaft and the Fuchs twin shaft. This is a mature technology and has been applied to a number of plants in both the US and Europe [18]. This process has the added advantage of increasing productivity by up to 33%, reducing electrode consumption by 40% and reducing dust emissions by 30% [18].

4.3.3. *Efficient casting and rolling methods*

Liquid steel must be cast into different shapes suitable for different uses. Following casting the steel is usually further shaped by either hot or cold rolling. The closer the cast steel is to the final product shape, the less energy that is consumed overall. This is because the steel does not have to be reheated in between the different stages of shaping. More efficient continuous casting has largely replaced traditional ingot casting.

Near net shape casting is more efficient because it combines the casting and rolling steps. Examples of continuous casting include, thin slab casting and strip casting. The application of near net shape casting is limited by the final product shape. Currently, less than 10% of production uses this method [20].

An emerging technology is the Castrip process, which offers potential energy savings of 80–90% compared to conventional slab casting and hot rolling. The Castrip process allows direct casting of thin strip from liquid steel and is more flexible, being able to tolerate a higher concentration of trace elements without loss of quality [18].

4.3.4. *Other energy efficiency improvements*

Taking a system-wide approach, improved process controls and maintenance can achieve further energy savings. For example, repairing air leaks from the sinter plant can reduce the power consumption of the fans by around 0.011–0.014 GJ/t sinter [20].

Programmed heating in the coke ovens can generate fuel savings of up to 10% with a payback time of 0.7 years [20]. Automation of the

Table 4
Energy savings and economics of key waste heat recovery options [18,20,39].

	Energy savings	Costs	Payback time	Source
Sinter plant heat recovery	55–120 MJ/t crude steel Electricity generated:1.1 MJ_e/t crude steel (0.31 kWh/t crude steel)	1.11$/t crude steel (capex)	2.8 years	[20]
COG recovery for coal moisture control	90 MJ/t crude steel		> 50 years	[20]
CDQ	450 MJ heat/t crude steel (160 MJ/t crude steel recovered as electricity) 250 MJ/t crude steel (coke savings in the blast furnace) 240–360 MJ steam/t crude steel (66–99 kW h steam/t crude steel)	35.5$/t crude steel (capex)	36 years	[20,39]
Top-pressure recovery turbine	Electricity generated: 44.6–116 MJ_e/t crude steel (12.5–32.1 kWh_e/t crude steel)	30.2$/t crude steel (capex)	30 years	[20,39]
BF heat recuperation	71–75.8 MJ/t crude steel fuel savings	2.05$/t crude steel (Type of cost not stated)		[18]
BOF gas recovery	535–916 MJ/t crude steel (depends on how the steam is recovered)	33$/t crude steel (capex and opex)		[18]
EAF scrap preheating using furnace off-gas	Electricity savings: 220 MJ_e/t crude steel (60 kW h/t crude steel) electricity savings	7.8–9.8$/t crude steel (retrofit capex)		[18]

Table 5
Energy savings from improved process control on an iron and steel plant [20,37].

	Energy or electricity savings	Capital costs	Payback time	Source
Sinter plant	Fuel savings: 11 MJ/t crude steel	0.05 $/t crude steel	1.4 years	[20]
Coke plant	Fuel savings: 50 MJ/t crude steel	0.12 $/t crude steel (retrofit)		[37]
Blast furnace	Fuel savings: 360 MJ/t crude steel	0.54 $/t crude steel	0.4 years	[20]
BOF			3 years	[20]
Hot strip mill	Fuel savings: 260 MJ/t crude steel	1.21 $/t crude steel	1.2 years	[20]
EAF	Electricity savings: 108–124 MJ_e/t crude steel (30–34.5 kWh/t crude steel)	1.03–1.62 $/t crude steel	0.5 years	[18,20]

hot-blast stove can payback within 0.4 years through fuel savings of up to 17% [20]. In the BOF, increased automation through a MultiGas Analyser with on-line feedback improves combustion efficiency, lowers operation costs and reduces maintenance [18]. Improved process control in the EAF also reduces electrode consumption by 25% [18] (Table 5).

A number of advanced processes for steelmaking are currently under development or demonstration. Current R&D programmes in the area of low-carbon steel include the COURSE 50 project, SCOPE 21 and the ULCOS programme. For example an advanced sinter plant design for new plants is the Lurgi emission optimised sintering process and advanced coke-making processes include SCOPE 21 and the Single Chamber System. SCOPE 21 is a Japanese design, which is more efficient, more productive and more flexible regarding the coal feed type [37]. The COURSE 50 project is also investigating advanced coking processes including catalysed COG reforming [37].

5. Cement

5.1. Description of the process

Cement is a commonly used binder, which when mixed with sand and rock aggregates, forms a strong and durable building material known as concrete. There are broadly two categories of cement: hydraulic and non-hydraulic cement. Hydraulic cements harden due to hydration of the material but once the reaction has occurred, the material retains its physical integrity even underwater. Portland cement is a hydraulic cement. By comparison, non-hydraulic cements must be kept dry (e.g. Gypsum) [40].

Ordinary Portland cement, which is currently the most widely used cement type, contains 95–100% 'clinker' [41]. Clinker is produced through the energy-intensive process of calcination of limestone in a cement kiln.

The raw materials required for clinker production are limestone, clay and sand. Following crushing and milling, correct proportions of the different raw materials are well mixed in an homogeniser.. The raw material is then fed to the kiln system [42]. The most common kiln type today is the rotary kiln. Modern kiln systems consist of staged pre-heaters, a pre-calciner and a rotary kiln. The pre-heaters dry and heat the raw material to the required temperature (around 900 °C). The number of pre-heater stages depends on the moisture content of the raw materials. In the pre-calciner the limestone is converted into lime (CaO), releasing CO_2 in a process known as 'calcination' [43]. Based on stoichiometry, 0.54 kg of CO_2 is produced for every kg of clinker. The mixture is then fed to the rotary kiln where it is fired with fuel burned directly in the kiln, achieving temperatures as high as 2000 °C [43]. At this high temperature, calcium oxide and silica in the sand react to form calcium silicates, forming a hard product, known as 'clinker' [40]. On exiting the kiln, the clinker is cooled, crushed and blended with gypsum to form cement [42].

The moisture content of the raw material has a direct impact on the energy requirements of the process and the type of kiln used. An out-dated method for processing raw material with a high moisture content (15–25%) is the wet rotary kiln. Here, additional water is added to the mixture to form a slurry of 30–45% water [44]. This is fed to the kiln where the water is evaporated and the limestone is calcined. Owing to the evaporation of the water, this process is very energy intensive and has largely been phased out. The semi-wet process aims to reduce energy consumption by removing water prior to the kiln by pre-filtering it. Wet and semi-wet processes have the advantage of improved product handling, more efficient raw material grinding and reduced dust. The Lepol rotary kiln is a semi-dry process, which was developed in the 1920s in Germany. Here the dry raw meal

is granulated by the addition of 11–14% water and preheated in a Lepol grate preheater prior to calcination [44]. The first dry kilns were called 'long dry kilns' as they were longer than kilns with preheaters [44]. Modern dry kiln systems consist of up to six staged pre-heaters and a pre-calciner in addition to the rotary kiln. An alternative to the rotary kiln is the older vertical shaft kiln. The shaft kiln was one of the first kilns designed to operate continuously. This is a popular kiln type for smaller operations in rural areas of developing countries such as China and India [45].

The production of clinker is the most energy intensive stage in cement manufacture. Additionally, large amounts of CO_2 are emitted as a result of the calcination reaction. If less clinker is used per tonne of cement, significant savings in both energy and CO_2 emissions can be achieved [46]. Hydraulic cements can be grouped into three main types: Ordinary Portland cement, Portland cement blends and non-Portland cements, with Ordinary Portland Cement being the most commonly used type, owing to its high compressive strength. Table 6 shows the typical composition of different Portland cement types. Ordinary Portland Cement contains the highest percentage of clinker. Fly-ash (waste residues from coal-fired power stations), the non-combustible parts of the fuel, and slag (mineral waste from iron production from iron ore) from blast furnaces can be mixed with clinker to produce blended cements [43]. This has the added advantage of avoiding the need for disposal of ash or slag waste.

5.2. Current status

Annual global cement production is currently around 3300 Mt and this is projected to increase to between 3700 and 4400 Mt by 2050 [48]. As shown in Fig. 11, cement production has doubled over the period between 1998 and 2009, largely due to China's production increasing by a factor of 3 over the same time period. China is by far the world's largest cement producer, accounting for 54.5% of global cement production in 2010, of which only around 1% is for export [49]. India, the US, Japan and Turkey are the next largest producers, together accounting for around 15% of global cement production [50].

Fig. 12 shows the total global energy consumption for the non-metallic minerals sector between 1972 and 2010 broken down by fuel type. Total energy consumption has more than doubled over the last three decades, increasing from ~5 EJ to ~13 EJ. This is largely due to the rapid increase in production in countries such as China and India over the same time period. Rapid urbanisation and development has resulted in a boom in the construction industry in these countries, increasing the demand for cement. Coal has become the major source of energy for this sector, increasing from 27% in the 1970s to 56% in 2010. China, in particular, relies heavily on cheap coal for cement production owing to huge domestic reserves.

5.3. Energy efficient technologies

The main ways in which energy usage and CO_2 emissions can be reduced in cement manufacturing are as follows:

- Phase out inefficient kilns and add pre-heaters and a pre-calciner to the efficient modern rotary kiln;
- increase the ratio of clinker substitutes in order to decrease process emissions arising from calcination; and
- introduce efficient milling and grinding equipment.

5.3.1. Phasing out inefficient kilns

The IEA estimates that total specific energy savings available in the cement industry is around 1 GJ per tonne of cement [47].

Table 6
Typical composition of different cement types [47]. Note percentages exclude gypsum, which is typically 5%.

	Ordinary Portland Cement	Portland—fly ash cement	Portland—Blast furnace cement	Portland—Pozzolanic cement
Clinker (%)	95–100	65–94	5–64	45–89
Fly ash (%)		6–35		
Blast furnace slag (%)			36–95	
Pozzolana (volcanic ash) (%)				11–55
Other constituents (e.g. clinker dust and other mineral additives) (%)	0–5	0–5	0–5	0–5

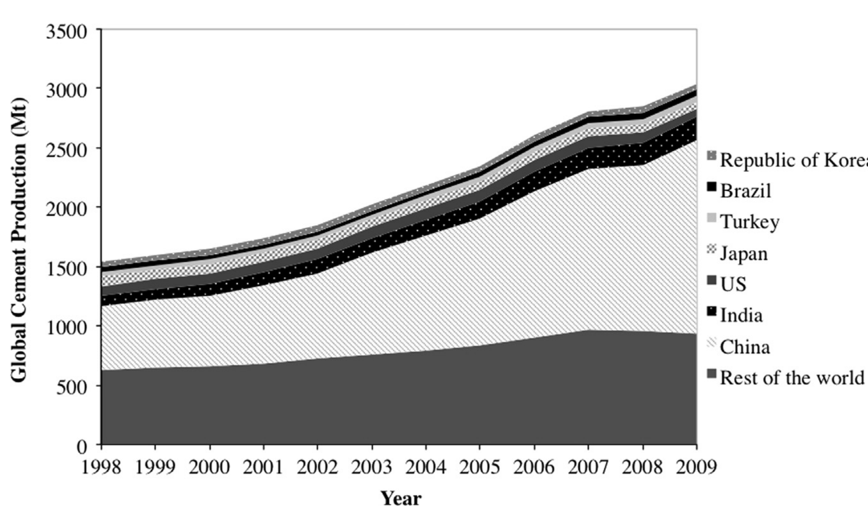


Fig. 11. Global cement production (Mt) between 1998 and 2009, showing contributions from top cement producing countries.
Source: US Geological Survey Data [50].

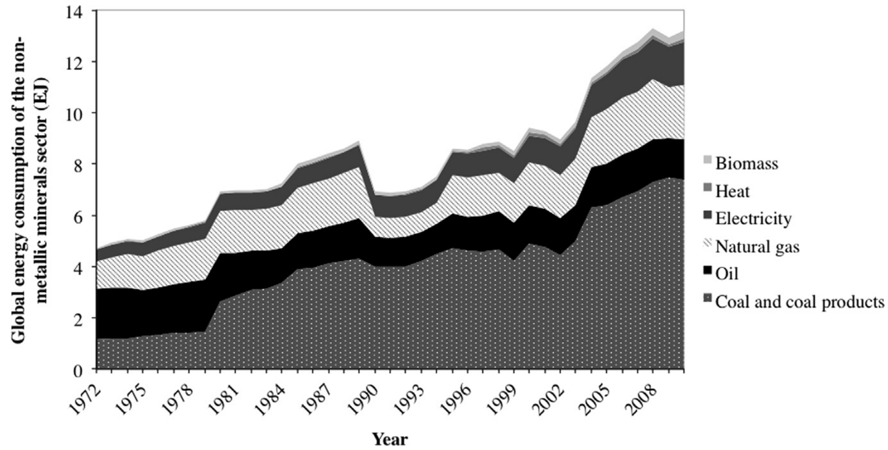


Fig. 12. Energy consumption by fuel type in the non-metallic minerals sector between 1971 and 2010. Based on data from the IEA Energy Balances [1].

Table 7
Energy intensity of different cement kilns [46,47,55].

	Final energy intensity GJ/t clinker
Vertical shaft kiln	3.7–6.6
Rotary kiln type:	
Wet (24–48% water)	6.0–7.1
Semi-wet (17–22%)/semi-dry (11–14%)[a]	3.8
Lepol (semi-dry)	3.7
Long dry process (0–0.7%)	4.3
Suspension pre-heater rotary kiln:	
1-Stage cyclone pre-heater	4.2
2-Stage cyclone pre-heater	3.8
4-Stage cyclone pre-heater	3.3
4-Stage cyclone pre-heater and pre-calciner	3.1
5-Stage cyclone pre-heater and pre-calciner	3.0–3.1
6-Stage cyclone pre-heater and pre-calciner	2.9

[a] Note that the value for the semi-wet/semi-dry kilns is underestimated because it excludes the energy required for drying.

Fuel savings, owing to the adoption of the most efficient kiln technology, make up the largest share of these savings. As for steel, China makes up the largest share (41%) of total energy savings potential in the cement sector. China has made significant progress in closing down of vertical shaft kilns. The share of vertical shaft kilns has decreased from 90% in 2000 to 40% in 2008 [51] and the latest numbers indicate that the remaining share is less than 10% [52]. Modern rotary kilns, some of them fitted with preheater and pre-calciner technologies, make up the remaining share. A recent study of the energy savings potential of 16 cement plants in the Shandong province showed that there is potential for primary energy savings of 12% and 23% compared to domestic and international best practices, respectively [51].

The theoretical minimum energy requirement for chemical and mineral reactions occurring during calcination in the kiln is between 1.6 and 1.85 GJ/t ([53] cited by [48]). However, unavoidable inefficiencies such as conductive heat losses through the kiln surface mean that such low energy consumption is unachievable in practice.

Table 7 shows the energy intensity of the different kiln types. Current BAT is the dry rotary kiln with a six stage preheater and a pre-calciner. Most new cement kilns are BAT, however the lifetime of a cement plant can be up to 50 years and so capital stock turnover limits the rate at which these savings potentials can be realised. In 2006, the share of clinker produced in wet kilns was 5.6% (in the Cement Sustainability Initiative Getting the Numbers Right regions). Cement production in wet kilns still continues in many countries making up the Commonwealth of Independent States [46].

Rotary kilns are more efficient than shaft kilns owing to economies of scale. Rotary kilns typically process around 60 times more cement compared to the average shaft kiln. Although rotary kilns have largely replaced the vertical shaft kiln, a large number are still in operation in China today. However, these are typically small-scale plants in rural areas and are rapidly being phased out. By 2015, almost all remaining vertical shaft kilns are expected to have been closed down [54].

The energy efficiency of the dry rotary kiln can be further increased by various heat integration and waste heat recovery options. For example: waste heat from the kiln exit gases, clinker cooler system and kiln pre-heater can be recovered and used to generate power. The most widely applied and economic option is the installation of a waste heat recovery boiler, running a steam turbine [56]. About 36–83 MJ_e/t clinker (10–23 kWh/t clinker) can be generated with an estimated installation cost of 3–4.50 \$/t clinker [56].

5.3.2. Clinker to cement ratio

According to current world best practice, the following substitutions can be achieved: for fly ash cement, up 35% can be substituted with fly ash; for blast furnace cement, up to 65% can be blast furnace slag. The global average clinker-to-cement ratio (this is the fraction of clinker in the cement) is 78%, however there is quite a wide spread depending on the location of manufacture. It is important to note that whilst clinker substitutes such as slag and fly ash reduce CO_2 emissions by reducing the amount of clinker required per tonne of cement, these substitutes increase the electricity requirements of the plant as they typically require a greater power input for grinding [48].

5.3.3. Efficient grinding and milling

Around 40% of electricity used in cement manufacture is used for grinding and milling [57]. Ball mills are the traditional method of grinding, accounting for around 60% of cement mills [57]. The remaining mills are made up of more modern mills, namely: vertical roller mills, roller presses and horizontal mills. These mills are more efficient and use between 30 and 40% less energy compared to the ball mill [56,57]. The choice of mill depends on the required grain size, clinker properties and final product quality.

Current grinding technologies are still highly inefficient with over 95% of the energy input being lost as waste heat [56]. Advanced comminution technologies include non-mechanical

milling technologies based on ultrasound, laser, thermal shock, electric shock or cryogenics [56]. These are still in the research phase and are still far from commercialisation.

6. Refining

6.1. Description of the process

Crude oil is a liquid mixture of hydrocarbons of varying shape and length, with a few impurities such as sulphur and nitrogen. By removing the impurities and separating out the different hydrocarbons according to boiling point (a process known as 'fractional distillation'), these products can be of much greater use. Furthermore, some of the hydrocarbons for which there is low demand (e.g. heavy fuel oil) can be transformed into more useful ones such as diesel and gasoline.

The most important process within a refinery is fractional distillation. In the crude distillation unit (CDU), crude oil is heated to approximately 370–400 °C at atmospheric pressure. The lighter fractions of the crude oil vaporise, and the heaviest ones remain as a liquid. The vapourised fractions move up the distillation column. There are usually about 30–40 'trays' within the column that collect liquid and allow gases to move higher up the column. The temperature in the column decreases with increasing height; at certain heights the temperature will be such that certain fractions will condense. Thus, the liquids in each of the trays are different, and are removed from the column as different products. The main products are (in ascending order of boiling point): petroleum gases, gasoline or petrol, naphtha, middle distillates, gas oil, the bottom fraction. The middle distillates include kerosene, naphtha and diesel oil [58].

The bottom fraction, which does not vapourise in the column, is sent to the vacuum distillation unit (VDU). This unit works in a similar way to the CDU, but is operated under a vacuum (0.1–0.15 bara) to reduce the boiling point of the fractions [58]. If this was done at atmospheric pressure, the temperatures would cause adverse thermal cracking reactions. This produces diesel oil, light fuel oil and heavy fuel oil.

Smaller refineries simply blend the fractions from the CDU and VDU to produce products suitable for sale. Larger refineries contain units which can crack or reform the fractions to reduce or enlarge them, respectively. This improves the products and also leads to a better distribution of products. *Hydrotreaters* react the naphtha fraction with hydrogen over a catalyst to produce a form of gasoline, which is then sent to a *catalytic reformer* to increase its octane level. The reformer produces hydrogen, which is used in other refinery processes. Fuel oil is sent to a *fluidised catalytic cracker* (FCC) to convert it to gasoline, diesel and lighter fuel oil. FCCs are net users of energy, although some is usually recovered in the catalyst regeneration step, through the combustion of CO produced from partial combustion of the coke which deposits on the catalyst. *Hydrocrackers* improve the yield and octane number of gasoline. Again, the hydrocracker is a net user of hydrogen. *Cokers* convert the heaviest fractions to lighter hydrocarbons and coke. The lighter products can be treated further in the other units of the refinery. The coke is gasified and used as a fuel within the refinery. The coker is a net user of fuel. The *visbreaker* is used to lighten the bottom products to fuel oils; it again is a net consumer of energy. The products of these units are then stored and blended before being sold on to consumers.

Fig. 13 shows the source of emissions arising from refineries. The dominating source of CO_2 emissions is from boilers and furnaces for both direct and indirect (using steam) heating applications. The regeneration of catalyst from catalytic crackers is the largest source of direct process emissions.

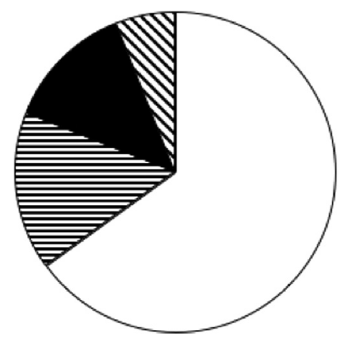


Fig. 13. Sources of CO_2 emissions from refineries in the UK [59].

6.2. Current status

Liquid hydrocarbon fuel demand increased from 66.3 million barrels per day (Mb/d) in 1990 to 87.4 Mb/d in 2011 (11.9 Mm^3) [6]. This increase in demand is mainly due to emerging economies such as China, while demand fell in OECD countries. Fig. 14 shows that the increase in refinery capacity reflected this trend, with 7.3 Mb/d of the 9.6 Mb/d global refinery capacity increase in the 2001–2011 period occurring in Asia Pacific [60]. Around 12.4 EJ/yr of energy is used by refineries [61].

In the short-term, energy savings can be achieved through improving the efficiency of heating (through heat exchanger network optimisation and fouling mitigation). Technologies that could play a role in the long-term include improved distillation technologies and carbon capture and storage (CCS). Energy efficiency improvements are discussed in more detail below, whilst CCS is dealt with in Section 9.

6.3. Energy efficient technologies

The sector-specific measures relating to the refining industry include:

- Efficient hydrogen use;
- Heat transfer improvements;
- Hybrid distillation systems.

6.3.1. Efficient use of hydrogen

Hydrogen is required by several processes [62] and is in high and increasing demand in refineries; indeed, it is sometimes imported from adjacent plants. It is usually generated by processes such as steam-methane reforming (SMR) which are 70% efficient [63], so generating hydrogen for combustion purposes is less efficient than burning methane. However, a large-scale gasifier to which CCS is applied could provide near zero-carbon energy, but would reduce the efficiency of the plant and increase capital and operating costs. Furthermore, this gasifier could be used to produce hydrogen for power generation at peak demand times and hydrogen for refining processes at off-peak times.

6.3.2. Heat transfer improvements

The evolution of refineries over time, as new processes are added, can lead to a previously optimised heat exchanger network becoming less optimal. Reviewing and altering the heat exchanger system can reduce energy requirements by a quarter [64]. However, the costs of these improvements, measured in terms of climate mitigation, are relatively high, at 119.3 to 217.5 \$/tCO_2 for fouling mitigation and 20.8 to 79.7 \$/tCO_2 for thermal energy management in Brazilian refineries [65]. Refineries which were

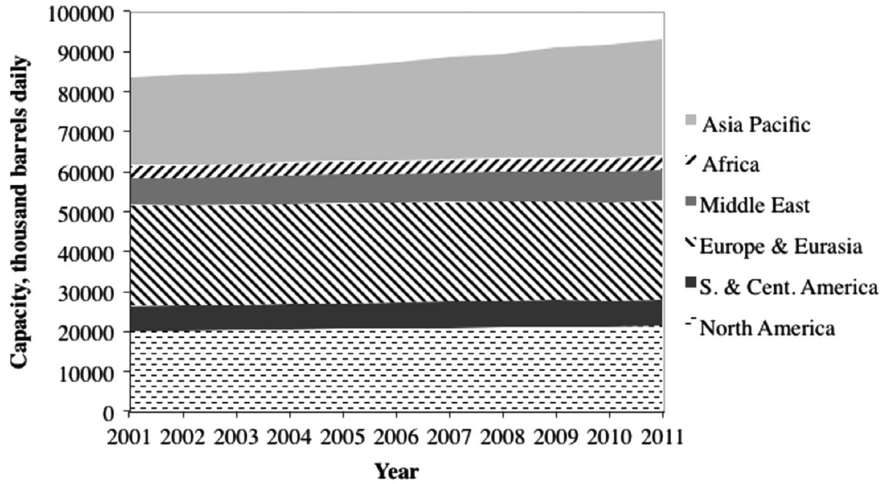


Fig. 14. Capacity of refineries between 2001 and 2011 adapted from [60].

originally well-integrated, such as those in most of Europe, will generally yield lower returns than those quoted above [66]. Paybacks of a year or less are possible for certain energy efficiency improvements in less advanced heat exchange systems [64,67].

Retrofitting furnaces can lead to 10–15% savings in energy use whilst being economically viable, according to a survey undertaken for the US Energy Star programme [68]. Some have suggested that this is a more efficient use of money than thermal energy management [69].

6.3.3. Hybrid distillation systems

By using distillation for a crude split of components into different streams and then other processes for purifying the streams to the necessary composition, the energy requirements of separation (often a third or more of the total refinery's needs) can be significantly reduced. These hybrid systems work on the principle that distillation reduces the stream size for the secondary 'polishing' step, reducing the capital and operating costs of those separation processes. The four main hybrid distillation systems, according to the US DoE [70], are:

- Crystallisation hybrid systems. These are currently in development stage for mainstream applications, but do have some specialised uses, such as xylene isomer separation.
- Membrane hybrid systems. These are popular and are used for azeotrope breaking and vent gas recovery. The energy savings can be around 33% [70,71].
- Extraction and absorption hybrid systems, used for alkene/alkane, acid/water and organic/water separations [72].
- Adsorption hybrid systems, used for hydrocarbon/water [73], alkene and aromatic separations.

7. Crosscutting technologies

Despite their diversity, industrial processes have a number of common equipment and systems. These include major steam systems, motor systems and opportunities for CHP. Such crosscutting technologies offer a useful target for energy efficiency programs.

7.1. Motor and steam systems

Driving motors and raising steam consumes a significant portion of energy in industrial processes. Around two thirds of electricity consumption in the industrial sector is used to drive motors [2]. Steam generation consumes 30% of global final industrial energy use [33]. Together, motor and steam systems account for 41% of total energy consumed in industry. Globally, the energy savings potential of industrial motor and steam systems remains largely untapped. It is estimated that the worldwide efficiency of motor systems and steam systems can be improved by 20–25% and 10%, respectively [33]. In the US, the estimated total energy savings potential through applying BAT in motors and motor systems [74] is between 15 and 25%.

Table 8 summarises the possible improvements to motor systems. Motor-systems are comprised of the motor itself and the motor-driven equipment - typically a pump, compressor or fan. The power consumption of the drive is dependent on the cube of the motor rotation speed, i.e. small changes in motor speed can result in large energy savings. Variable speed drives (VSD) can be used to control the motor speed in response to changes in demand loads. Energy savings of 10–20% can be achieved through VSDs. If a VSD is replacing poor practice such as throttling, energy savings could be as high as 60%. It is important to note that only motor systems where the demand load is highly variable will benefit from VSDs. Table 9 summarises specific examples in both the iron and steel and cement sectors where VSDs can offer significant savings. Over-design of driven equipment, resulting in equipment operating below their peak performance efficiency, is another major source of wasted energy. Improved maintenance practices are essential for reducing system losses. Leaks in compressed air systems can account for 20–30% of compressor output [74]. Switching to premium lubricants can offer energy savings of around 3%. Although many smaller motors have sealed bearings, around half of the motors in industry are serviceable by the customer and can benefit from premium lubricants [74].

Similar improvement options exist in steam systems. These can be divided into energy efficiency measures for (i) boilers and (ii) heat distribution. The efficiency of steam boilers depends on the design and fuel. In China, for example, average boiler efficiency is 60–65% (by comparison, a well-designed coal-fired boiler can achieve an efficiency of ~84%), largely due to poor quality coal and incomplete combustion [33]. Table 10 summarises the potential measures for improving energy efficiency in steam systems. Measures such as improved insulation and steam trap maintenance can offer large energy savings and are easy to retrofit and are relatively cost effective with estimated payback periods of less than 1.1 years (assuming a discount rate of 30%). It has been estimated that, in the US in 2001, there existed cost effective improvements to steam systems, which could provide annual energy savings of up to 1258 PJ per year. This is equivalent to

Table 8
Improvements to motor and steam systems.

Improvements	Description/examples	Potential energy savings	Costs and barriers
System design optimisation	Matching motor service and work demand. All components should be optimised to minimise demand and increase efficiency	17–25% [74]	Typically lack of awareness and/or expertise
Efficient control strategies to respond to load variations	e.g. Variable Speed Drive (VSD)	10–20% [33] and even up to 60% especially when replacing poor practices such as throttling	Lack of awareness Most systems are not evaluated on a life-cycle basis (i.e. maintenance, reliability etc. not considered)
Reduced demand for energy services	e.g. substituting a blower for compressed air Turning off steam to inactive equipment		
High efficiency motors	e.g. Superconductive motors Permanent magnet motors Copper rotor motors Switched reluctance drives Written pole motors Very low loss magnetic steels	1–10% Decreased losses by 20–30% [74]	Motors often repaired rather than replaced Superconductor motors & Copper rotor: costs still high PM Motors & WP motors: Information, dissemination and demonstrations required
Improved maintenance practices	Establish a maintenance program		
Reduced system losses	**Pumps**: Fix leaks, damaged seals and packing Repair/replace valves with more energy efficient designs **Compressed air**: Replace or repair air filters Replace or upgrade condensate drains		
Re-design of equipment driven by motor	Over sizing Replacement of inefficient equipment		

Table 9
Example savings from improved motor systems in the iron and steel, cement and refinery sectors.

Sector	Details	Payback	savings	Source
Iron and steel	COG compressors	21 years	6–8 MJ/t coke	[20]
	BOF ventilation fans		3 MJ/t crude steel	[20]
	EAF flue gas fans	2–3 years	60 MJ/t	[20]
Cement	AC motor on Kiln drive		0.5–1% less electricity to drive kiln	[56]
	VSD for Kiln fan		40% reduction in motor electricity consumption	[56]
Refineries	Advanced pumping system		50% reduction in pump electricity consumption	[76]

Table 10
Improvements to steam systems [77].

Improvements	Measure	Fuel savings	Implementation potential	Payback period (years)
Boilers	Improved process control	3%	59%	0.6
	Reducing flue gas quantities	2–5%	–	–
	Reducing excess air	1% per 15% less excess air	0%	–
	Improved insulation	6–26%	–	Unknown
	Improved maintenance	10%	20%	0
	Heat recovery from flue gas	1%	100%	2
	Recovery of steam from blowdown	1.3%	41%	2.7
Distribution systems	Improved insulation	3–13%	100%	1.1
	Improved steam traps	Unknown	–	Unknown
	Steam trap maintenance	10–15%	50%	0.5
	Automatic steam trap monitoring	5%	50%	1
	Leak repair	3-5%	12%	0.4
	Flash steam recovery/condensate return	83%	–	Unknown
	Condensate return	10%	2%	1.1

7% of final energy consumption in US industry and would result in CO_2 emissions reductions of 45–48 Mt CO_2 per year. More recently, the IEA [33] gives a more conservative estimate of energy savings in the US of around 500 PJ per year, possibly indicating that opportunities for savings in steam systems have been realised.

The advantages of efficient motor and steam systems include: increased competitiveness and reduced consumption of fossil fuels. Improved system reliability and control and reduced maintenance costs through reduced wear are some additional benefits. The reason these apparently obvious potentials remain unrealised is because

achieving these energy savings requires a system-wide approach, which is often difficult in large organisations. High energy efficiencies have been reached for individual components such as motors (85–96%) and boilers (80–85%) but the efficiency of the overall system is often much lower. Essential to improving overall efficiency is designing a system where supply and demand are properly matched. Highly efficient pumping of fluids, compressing of air and generation of steam is wasted if these are in excess of the plant requirements. Often this requires hiring an expert to analyse and optimise the overall system. Losses occur at every stage in the process, however with careful design and management these can be minimised. In particular, proper operation and maintenance procedures must be established.

7.2. Combined heat and power (CHP)

Thermal generation of electricity always results in the production of some low grade heat. Depending on the efficiency of the plant, between 40 and 80% of the energy generated in power plants is dissipated in the form of hot air or water. Instead of wasting this energy, the heat can be used to raise steam for industrial processes or hot water for district heating, depending on the temperature. This simultaneous production of heat and power (electricity) is known as combined heat and power (CHP), sometimes also referred to as 'co-generation'.

In terms of fuel efficiency, CHP is always an improvement on conventional power generation. Energy savings of at least 10%, and typically higher are achievable [75]. CHP can reach overall efficiencies in excess of 80%. This decreased energy intensity has significant advantages beyond CO_2 emissions reduction: reduced fuel usage can have cost savings of between 15 and 40% compared to grid-sourced electricity and heat generated by onsite boilers [78]. This translates into improved competitiveness for industry and businesses, alleviates fuel poverty and lowers the cost of delivery of public services. In addition, reduced demand from centralised power stations decreases the stress on grid.

The idea behind CHP is not a new one. The technology is proven and reliable and has an established supplier base. It is also versatile and can be applied to a wide range of industries. In some countries, such as Finland, CHP is used widely. 90% of urban buildings in Finland are linked to a district heating system and 38% of the country's electricity is generated in CHP plants. CHP has penetrated certain industries more than others. The Chemicals and Petrochemicals industry and the Pulp and Paper industry are particularly well suited to CHP, and together account for 20–40% of industrial CHP capacity. Refineries are also promising candidates and as such already have large amounts of CHP installed [79]. The estimated mitigation potential of CHP in industry is 150 Mt CO_2 in the USA and 334 Mt CO_2 in Europe [80]. However, although the benefits of CHP are widely recognised, the global implementation of CHP is still low. This is largely due to the fact that a suitable use for the generated heat needs to be found within reasonable proximity to the power generation plant; for example, to date the longest district heating pipeline exists in Sweden and is 28 km [81]. In addition, the current preference for large central power stations to generate electricity means that there is often no easy local use for waste heat energy.

Owing to the increased complexity of the process, the capital cost of a CHP plant is higher than a conventional power plant [2]. In drawing up CHP projects, there are often regulatory requirements, which increase the commercial and operational complexity. Typically, a long-term heat and power contract is required with the host site, which often means that there is an increased risk of deal collapse. In general, lack of awareness of the opportunities and insufficient training on how to implement them hinder the penetration of CHP technologies. A system-wide perspective on the development of CHP plants is often lacking.

8. Summary of important measures and energy savings potential

Some of the most important measures for reducing energy demand in industry are shown in Table 11.

The overall energy savings potential for the iron and steel and cement sectors are shown in Table 12. These are taken from a study done by the IEA in 2006. Given the improvements in basic efficiencies in recent years, particularly in countries such as China, it is expected that these figures are somewhat reduced. Unfortunately, to date, the IEA has not updated these figures.

9. Beyond energy efficiency in industry: Options for further decarbonisation

The industrial sector is made up of a diverse range of processes and product manufacture. There is therefore no single technology on which to focus our efforts. A piecewise approach to reducing emissions is required, which is challenging to monitor, incentivise and control. In order to significantly reduce industrial emissions beyond energy efficiency improvements, the following key actions are required:

(a) *Demonstrate and deploy fuel and switching to low carbon energy sources;*
(b) *Accelerate research into industrial CO_2 capture and rapidly demonstrate integrated industrial CO_2 Capture and Storage (CCS) plants;*
(c) *Co-location of industries to use energy more efficiently;*
(d) *Alter product design and waste protocols in order to facilitate reuse and recycling in order to close the materials loop.*

Table 11
Summary of important measures for energy efficiency in industry.

Industry	Measure	Energy savings	Cost
Iron & Steel	BOF gas recovery	535–916 MJ/t crude steel (depends on how the steam is recovered)	33 $/t crude steel (capex and opex)
	EAF scrap preheating using furnace off-gas	220 MJ_e/t crude steel (60 kW h/t crude steel) electricity savings	7.8–9.8 $/t crude steel (retrofit capex)
Cement	Phasing out inefficient kilns	Up to 3700 MJ/t clinker	
	Waste gas recovery boiler	36–83 MJ_e/t clinker (10–23 kW h/t clinker)	3–4.50 $/t clinker
Refining	Altering heat exchanger networks	Up to 25% of refinery energy demand	20.8 to 79.7 $/t$CO_2$
	Hybrid distillation systems	Up to 33% of energy demand of specific separation processes	
Cross-cutting technologies	System design optimisation	17–25% of system energy demand	
	Improved insulation	Up to 26% energy demand	1.1 year payback period

Table 12
Global total energy savings potential for the iron and steel and cement sectors based on best available technology in 2006 [82].

	Total global energy consumption (PJ)	Energy savings potential (PJ/yr)	Savings potential (GJ/t product)	Percentage savings (%)	Technologies
Iron and steel	14,560	5000	4.1	34	Steel finishing improvements; Efficient power generation from BF gas; switch from OHF to BOF; increased BOF gas recovery; Blast furnace improvements; COG recovery; CDQ
Cement	12,380	2500	1.0	20	Fly ash and other clinker substitutes; blast furnace slag; electricity savings; fuel savings

9.1. Fuel switching

Fuel switching includes the following options: (1) switching to less carbon intensive fuels such as replacing coal with natural gas; (2) co-firing with, or switching to waste and biomass; (3) switching to decarbonised electricity; and (4) switching to hydrogen (provided the hydrogen is produced via a low CO_2 process, for example using decarbonised electricity to electrolyse water). According to IEA projections, fuel and feedstock switching could provide emissions savings of 0.95 $GtCO_2$ against business-as-usual projections by 2050 [82].

Of the major fossil fuels, coal has the highest emissions factor relative to its available energy: 96 kg CO_2e per GJ. The emissions factor of natural gas by comparison is just over half that of coal: 51 kg CO_2e per GJ. Thus replacing coal with natural gas can significantly reduce emissions. This does, however, depend on the gas source and method of production. One recent lifecycle study indicated that the CO_2 intensity of shale gas 'fracking' is higher than for conventional gas and possibly even higher than that of oil and coal. This is owing to fugitive emissions of methane released during the shale fracturing process [83]. When this is considered, another study found that the greenhouse gas footprint of shale gas is similar to that of coal over a 20 year timeframe and between 0.61 and 0.88 of that of coal over a 100 year timeframe [84].

In the iron and steel sector, pulverised coal injection is an example of switching to a less carbon intensive fuel. The coal replaces coke usage in the blast furnace. There is a limit to how much can be substituted, however, due to the structural role that the coke plays in the furnace. Payback times for the injection of alternative fuels in the blast furnace depend on the type of fuel but range from between 1.3 and 2.4 years [20]. In Brazil, charcoal is used in small-scale blast furnaces instead of coke [85]. Charcoal is mechanically unstable compared to coke [37] so substitution is limited to around 20% [2]. Waste fuels can be used as a fuel for the sinter plant. Owing to reduced fuel costs, this option can be economically viable; a payback time of 0.5 years has been reported in some cases [37]. Japan has increased its use of waste plastic in the iron and steel industry from 0.46 Mt in 2005 to 1 Mt in 2010. Germany and Austria also make use of their waste plastics [2]. Additionally, methane, CO or H_2 produced from biomass would also reduce emissions from the blast furnace [39]. Biomass or waste can also replace the fossil fuels used in heating furnaces. The efficiency of these processes can be improved by gasifying the biomass first. Estimates indicate that around 10% of the fuel could be substituted [39].

Natural gas firing of cement kilns is technically feasible and is carried out in a number of countries where gas supply is plentiful and cost-effective [46]. However, in most regions natural gas firing of cement kilns is prohibitively expensive. However, future game-changers such as shale gas and a high carbon price could make it more economically attractive. Cement kilns are particularly suited to the incineration of waste; the high incineration temperature, alkaline environment, residence time and good mixing of gases and products ensure that the waste is safely disposed of with minimal environmental impact. Since the 1990s, a wide variety of waste fuels have been co-fired in cement kilns [2]. In 1990, fuel substitution was around 3% in the EU, equivalent to 1.7 Mt CO_2 avoided. This increased to around 17% in 2004, or 9.7 Mt CO_2 avoided [86]. The WBCSD Getting the Numbers Right Program indicates that in some European countries, the average substitution rate for the cement industry is over 50% [48]. There is still a large potential for waste co-firing in China, where currently very little waste fuel is burned in cement kilns. Since energy costs account for around a third of cement production, substituting expensive fossil fuels with wastes has the added advantage of reducing the cost of cement production.

Switching to biomass can offer significant emissions savings; biomass is considered carbon neutral under the European Emissions Trading Scheme (ETS), i.e. it has a net emission factor of zero (whether or not biomass is carbon neutral depends on its production and transportation). The disadvantage of replacing fossil with biomass fuels such as charcoal is that they can compete with the agricultural sector for food production (although this can be addressed, at least in part, by using only agricultural residues and certain crops which do not compete). Additionally, converting virgin rainforest into arable land releases large amounts of CO_2 and also reduces biodiversity. The transition from fossil fuels to waste and biomass is not a simple switch. Careful consideration must be given to the properties of the substitute fuel. The high content of alkali metals, typically found in biomass ash, can pose problems at high temperatures, resulting in agglomeration and fusing of the solid material. Waste fuels such as municipal solid waste often contain high concentrations of heavy metals such as mercury and lead. In the EU, the regulations for the combustion of waste are set out in the Incineration of Waste Directive [87].

The share of electricity making up the industrial energy mix has increased from around 14% in the 1970s to roughly 25% today [1], but the options for further electrification of industry are currently limited. For example, steel manufacturing in an electric arc furnace is limited by the availability of cheap electricity and the supply of steel scrap. Research is currently underway to develop a method of primary iron production using electrolysis; however, at present the energy requirement is extremely high. In the future, a process that uses hydrogen as a reducing agent in the blast furnace could also be envisaged [88] provided the hydrogen is produced using a low-CO_2 method. Hydrogen can also be used to directly reduce steel. Reduction can take place in direct reduction reactors or more advanced flash reactors [88].

9.2. Carbon capture and storage

In the EU alone, around 25% of emissions which are addressable by CCS are from industrial sources. This amounts to 0.5 Gt, based

on 2007 figures [89]. Additionally, for industrial process emissions (such as CO_2 emissions arising from calcination of limestone), capturing the CO_2 and sequestering it is the only option for avoiding these CO_2 emissions to atmosphere.

Industry provides some unique opportunities for the early demonstration of CCS. These include:

(1) Separation of CO_2 is a routine process in some industries. Examples of such processes include the production of hydrogen, ethylene, ethanol and ammonia, natural gas processing and coal-to-liquids. These processes typically produce streams with a high concentration (30–100%) of CO_2, lowering the cost of separation to about half that of capture from a power plant. Although the emissions from these processes make up a small share of total emissions from industry, due to lower costs, these processes could play an important role in the early demonstration of CCS technology.
(2) Industrial sites are often some of the largest stationary sources of CO_2 emissions in the world (Table 13). This results in improved economies of scale for CO_2 capture. Large steel plants can consist of up to five blast furnaces each with a production capacity of 3 Mt/yr and each emitting around 3.5 Mt CO_2 per year, a total of 17.5 Mt CO_2 per year. This compares to a 500 MW coal-fired power plant, which emits around 3.8 Mt CO_2 per year.

According to the IEA, CCS will need to make up 33% of emissions reduction in industry by 2050 [2]. Of this, more than 80% of the CO_2 captured from industrial sources is projected to be from iron and steel and cement. With the remaining CO_2 captured from chemical and petrochemical processes, mostly from refineries and ammonia production, and the pulp and paper industry.

The cement sustainability initiative recommended in 2009 that there should be demonstrations of CCS applied to cement kilns by 2015 and that by 2050, 50% of all new cement kilns should be equipped with CCS [48]. CCS from industrial sources is in the R&D phase but could reduce annual emissions by around 1.75 $GtCO_2$ against business-as-usual by 2050, according to IEA projections [2]. Continued and focussed investment and R&D is required to reduce the costs of industrial CCS if commercial deployment between 2020 and 2030 is to be realistic.

9.2.1. *Capture technologies from industrial sources*

To date, the focus of CCS research has been on CO_2 capture from power plants and limited attention has been given to its application in the industrial sector. The activity in this area is growing however with a number of publications focussing on CCS applied to industrial sources [91–93].

Research in the area of CCS from iron and steel production is being carried out by the Ultra-Low CO_2 Steel (ULCOS) programme [88]. A number of alternative iron and steel production processes, which enable the capture of CO_2, are currently under investigation.

The gas exiting a conventional blast furnace (BF) contains around 20% CO_2, 21% carbon monoxide (CO) and the balance nitrogen (N_2) and hydrogen (H_2) and some water (H_2O). The CO_2 concentration can be doubled by using the so-called 'shift reaction' to convert CO and H_2O to CO_2 and H_2. This allows physical solvents, already developed for pre-combustion capture in the power sector, to become technically feasible. Alternatively, oxygen, rather than air, can be injected into the BF. The gas exiting the BF would be nitrogen free and the CO_2 can be separated more easily. The remaining CO and H_2 are recycled and injected at the bottom of the blast furnace, where they act as reducing agents. This technology is known as top gas recycling (TGR) and has the additional benefit of decreasing the amount of coke requirements of the BF [91]. Natural gas-based DRI can also be modified to include CO_2 capture [88]. Prior to entering the DRI reactor, natural gas enriched with H_2 from the CO_2 capture process, is partially oxidised to synthesis gas (CO and H_2) by reacting it with oxygen. This reducing gas is then fed to the DRI reactor. The gas exiting the DRI reactor contains a mixture of CO_2, CO and H_2 and H_2O. As with TGR, the CO_2 concentration is increased via the shift reaction and the CO_2 can then be separated using solvents.

Table 13
Properties of candidate gas streams for application of capture technologies. Comparison of industry and power sources, demonstrating the transferability of CCS technology developed for the power sector to industry [135].

Source	Average emissions/source (Mt of CO_2 per source)	No. Of sources in 2005	CO_2 concentration of the stream for capture (dry volume %)
Power station flue and fuel gas			
Natural gas fired boilers	1.01	743	7–10
Gas turbines	0.77	985	3–4
Oil fired boilers			11–13
Coal fired boilers	3.94	2025	12–14
IGCC: after combustion			12–14
IGCC: synthesis gas after gasification			8–20
Upstream processes			
Natural gas sweetening	NA	NA	2–65
Chemical and petrochemical			
Refineries	1.25	638	3–13
Ammonia	0.58	194	18
Hydrogen			15–20
Methanol			12
Ethylene oxide	0.15	17	8
Iron and steel			
Blast furnace gas before combustion	3.5	180	20
Blast furnace gas after combustion			27
Cement			
Cement kiln exhaust gas (using air)	0.79	1175	14–33
Cement kiln exhaust gas with oxy-fuel			> 80

The European Cement Research Academy is currently conducting research on the application of CCS technology to the cement industry. Additionally, CEMEX was a partner in the EU-funded C3-Capture project and was working together with academics to further develop this process. The company has US DOE funding for a calcium-looping pilot plant in Monterrey to investigate the economic and technological feasibility of this process [94].

Post combustion capture of CO_2 from the cement industry uses the same technologies as those in the power sector and can easily be retrofitted to existing plants, albeit at high cost. Oxy-fuel combustion is a highly promising capture technique for the cement industry. However, oxy-fuel combustion results in increased kiln temperatures, which can damage the kiln lining. This can be avoided by dilution with recycled CO_2; the effects on the chemistry of the process need to be investigated. The prevention of air intrusion is another difficulty, which must be overcome [95]. A promising alternative to organic solvents for post combustion capture is the use of calcium oxide as a solid CO_2 sorbent [96]. Flue gas from a cement kiln is reacted with calcium oxide (CaO) to produce calcium carbonate ($CaCO_3$) at around 680 °C. In a second reactor, the calcium carbonate is calcined at around 900 °C, producing a pure stream of CO_2 for sequestration. The resulting calcium oxide is recycled back to the first reactor. The overall efficiency penalty of this process is lower than for conventional post combustion capture using amines. Additionally, there is a unique synergy with cement manufacture: the spent CaO from the capture plant can be used to make cement clinker, reducing the need for limestone calcination and saving around 50% of the emissions of cement manufacture by this substitution alone [96].

CCS is possible in many refinery locations, with potential costs from 38 to 134 $\$_{2011}$/t of CO_2 avoided [92]. CCS is very important for long-term cost-effective mitigation of CO_2 within this sector, with savings of 3.78 Mt CO_2/yr estimated for a "realistic" no-CCS scenario with decarbonised electricity available (and these savings coming exclusively from technologies other than electrification), vs. 10.58 Mt CO_2/yr from a realistic scenario where CCS was employed (total baseline emissions 18.17 Mt CO_2/yr) in the UK alone [16].

The production of process heat in boilers and furnaces are responsible for 30–60% of CO_2 emissions from refineries and are candidates for post-combustion and oxy-fuel combustion capture technologies. Redirection of CO_2 from the various combustion units to a central CO_2 capture unit has been suggested [97] but concerns remain about whether this is possible. In reality, smaller capture plants may be put on the largest stacks only, eliminating this uncertainty but probably increasing the capture cost [98].

Hydrogen production accounts for 5–20% of CO_2 emissions, but these are relatively high purity and pressure, permitting cheaper capture per tonne of CO_2 than from the boilers and furnaces. Capture from steam methane reforming (SMR) plants tends to use chemical solvents such as methyl diethanolamine (MDEA), but physical solvents can be used to capture CO_2 from gasification plants due to the higher pressures involved. Capture from pressure-swing adsorption plants is more difficult due to the large amount of impurities (20–30%). Furthermore, this stream is often used as a fuel, reducing the CO_2 concentration [99].

FFC units can account for over half of CO_2 emissions from refineries [100], and are process-related. Concentrations tend to lie between 10% and 20% [101]. Post-combustion capture is the most developed technology in this field but oxy-fuel combustion is a potential rival.

9.3. Co-location of industries

Industrial symbiosis is the sharing of a by-product or service that would otherwise have been disposed of or underused in order to minimise waste and maximise the utility of resources. The first discovered example of this was the Kalundborg eco-park (Denmark), which saves between $12 and 15 million per annum [102] as well as more than 150,000 t of CO_2 per annum. Heat integration of processes can reduce energy demand quite significantly; three Japanese prefectures were calculated to have been able to save up to 37%, 24% and 71% of their industrial energy demand through co-location and industrial symbiosis [103], and refineries could save up to 20–25% [66]. In practice, high-temperature processes produce medium-temperature heat streams which can be used by medium-temperature industries, and likewise for medium- and low-temperature industries. Determining a 'fair' method of distributing financial savings is difficult, but they are often based on heat or economic value. It has been suggested that game theory provides a strategy for delivering returns to partners that maximise the probability of all partners having sufficient incentive to stay within the symbiotic network [104].

9.4. Lifecycle options

Whilst the above sections highlight a wide range of available technologies for reducing emissions from industry, approaching 'zero-carbon production' is difficult, if not impossible without taking a lifecycle and system-based approach to production and consumption in industry. The Waste and Resources Action Programme (WRAP) highlights 'resource efficiency' and 'resource sufficiency' as two complementary approaches for achieving sustainable manufacturing. Resource efficiency means producing a product with the same functionality, whilst minimising the resource inputs and environmental impact over the lifecycle of the product. Resource sufficiency involves reducing the demand for the product.

Recycling of products such as metals, plastics and paper can offer significant energy savings. The level of recycling, which can be achieved depends on the lifecycle of the product and material flows. Once manufactured, steel and aluminium can take around 100 years before becoming available as scrap. This is particularly relevant for developing countries, which are still building up their infrastructure and have not reached a steady state of material flow. Currently, the EU is increasingly exporting significant amounts of waste to China and other Asian countries. This has arisen due to strict EU environmental and health rules making waste disposal and recycling expensive, combined with cheap transport (container ships might otherwise return empty to China) and high demand in China. The government funded research programme, WellMet2050 [90], is suggesting going one step further and encourages 'reuse without melting' of scrap rather than recycling. Although the production of aluminium and steel from recycled scrap is much less energy intensive compared to production from ore (around 40% less for the case of steel and 20 times lower for that of aluminium), the high melting temperatures of these metals mean that recycling is still an energy intensive process (around 10 GJ/t). By comparison, reusing metals without melting them has negligible energy requirements. Three sources of metal that offer immediate savings of 2 Mt CO_2 in the UK with minimal investment costs are the reuse of (i) structural steel in construction, (ii) manufacturing scrap (leftovers and offcuts) and (iii) aluminium swarf (shavings and chippings of metal resulting from cutting, grinding and milling) bonded together at low temperature.

The World Steel Association [105] is actively promoting 'designing for purpose', such as the use of advanced and ultra high-strength steels in the manufacture of cars and trains. In doing so, automotive manufacturers can reduce the mass of the vehicle by 17–25%, while maintaining safety standards. This means reduced steel requirements and hence reduced emissions from steel production. In addition, the lighter vehicle requires less fuel. If all vehicles worldwide (approx 71 million produced in 2008 alone) were made of high-strength steels this would result in total lifetime emission [106] saving of 156 MtCO_2e.

Many energy intensive construction materials will play a key role in a low carbon future through their role in building renewables. Around 45 t of cement and 120 t of steel are required per MW of onshore wind power. This increases the urgency for reducing the emissions intensity of these materials. Wind turbines built from highly emission-intensive cement and steel take around 6 to 8 months of operation before they 'cancel out' the CO_2 embodied in their manufacture [107].

In many applications, conventional materials can be replaced with alternative low-carbon or renewable materials such as biomass. In the construction industry, wood is a strong and versatile material for replacing conventional materials such as cement and steel. There is a rising trend of using straw as an insulating material in buildings. In many cases, plastic packaging can be replaced with paper or card. The bio-plastics industry has grown rapidly in recent years [108], increasing by around 40% per year to 0.36 Mt in 2007. This is still only 0.2% of global petrochemical plastics production. It is estimated [108] that the technical potential for substitution (considering application only and not resource availability or economics) is around 240 Mt or 90% of global consumption of plastics and fibres in 2007. However, for bio-plastics production to reach these levels, challenges such as high production costs and low performance need to be overcome. Furthermore, as with biofuels, biomass sources must be carefully selected to avoid competing with agricultural land for food production.

A number of synergies between industries exist. One tonne of steel produces between 200 kg (EAF route) and 400 kg (BF/BOF route) of by-products. These slags, dusts and sludges contain a mixture of silica and oxides of calcium, magnesium, aluminium and iron. Over recent years, the usefulness of these supposed waste streams has been identified and a large percentage is recovered and used either within the steelmaking process or sold to other industries. The uses of these by-products include as a construction aggregate, concrete products, clinker raw material, road bases and surfaces and roofing. Use of waste materials in connection with carbon capture and storage is also possible; for example, *Carbon8 Systems* has developed an accelerated carbonation process to sequester CO_2 and at the same time treat hazardous wastes such as slags and contaminated soils [109]. High electricity users such as steel EAFs and aluminium smelters might also play a role in dealing with intermittency from renewable power generation. Provided that these plants are sufficiently flexible, they could be run when there is excess supply from renewable and powered down during supply shortages.

In the long-term, continued consumption of manufactured goods at current rates raises serious sustainability concerns. In addition to CO_2 emissions, industrial activity places strain on the environment through extraction of natural ores, disposal of wastes and consumption of other precious natural resources such as water. Resource sufficiency aims to reduce consumption of manufactured goods through various means, such as: designing products to last, ensuring products are used for their full lifetime, encouraging the hire of equipment rather than private ownership and making best use of existing infrastructure. Achieving the goals of resource sufficiency is likely to require a major shift in industry structure and focus, as well as in consumer behaviour. There are still huge uncertainties as to how a resource sufficient world would operate and how to reach this goal.

10. Policies to unlock industrial energy efficiency and further abatement of CO_2 emissions from industry

As already discussed, several technology options at a range of costs exist to mitigate CO_2 emissions from the iron and steel, cement and refining industries. Moreover, these energy- and carbon-intensive industries are likely to face increased costs as a result of taking up some of the available mitigation technologies (although measures such as certain energy efficiency improvements can be cost-reducing), and their products are in general traded in globally competitive markets, so increased production costs in one region compared to others with less stringent mitigation policies could have unfavourable competitiveness impacts. Together these considerations mean that careful policy planning and implementation are required in order to realise these industries' mitigation potential whilst avoiding adverse economic impacts. Industry mitigation policies fall into four key categories:

- Establishing energy and emissions monitoring systems;
- Overcoming barriers to the take-up of cost-saving energy efficiency measures;
- Incentivising the uptake of fuel-switching and lower-cost abatement measures through carbon pricing, subsidies or other economic instruments;
- Supporting Research, Development and Demonstration efforts to establish new, pre-commercial mitigation technologies.

10.1. Industrial energy and emissions monitoring

A policy priority in many countries is to establish a robust basis for monitoring industry energy consumption and emissions (both in absolute terms and per unit product). Many developed countries already have detailed industrial energy consumption statistics as part of their greenhouse gas monitoring and policy frameworks, for example the UK's Digest of UK Energy Statistics (DUKES) [111]. Many developing countries are working towards improved monitoring. For example India's new Perform, Achieve and Trade (PAT) energy efficiency scheme for energy-intensive industry requires detailed energy audits of included installations [110]. In addition, international initiatives exist to implement better energy and emissions reporting, as discussed in the roadmap section of this paper. Such initiatives are an important component for informing policy makers of current energy and emissions data and establishing benchmarks for the best practice standards against which industries can aim to improve their efficiency.

10.2. Energy efficiency policies

In all world regions, energy efficiency in manufacturing industries has improved over recent decades, driven largely by the improved economics of more efficient technologies as new plants have replaced old ones, and as plants have increased in size (which often improves efficiency) [33]. Nevertheless, a range of policies has been implemented with the aim of accelerating such efficiency improvements.

For example in the UK the Climate Change Levy (CCL) was introduced in 2001, as a tax on energy use by businesses. Energy-intensive industries covered by the CCL (including iron and steel, cement and chemicals manufacturers) are eligible for entering into Climate Change Agreements (CCAs), whereby they agree with Government two-yearly targets for improving their energy efficiency or lowering their carbon emissions—if they meet the targets they receive a significant discount on the CCL [112]. There is evidence that the introduction of the CCL with CCAs led to energy efficiency improvements in many of the industries covered fairly quickly, with the steel, cement and chemicals sectors all outperforming their energy efficiency targets in 2002 [113]. Similar evidence comes from experience in other countries, for example Denmark in the 1990s, where an energy tax with energy efficiency agreements produced notable (in excess of 10%) reductions in industry energy usage [114]. More recent evidence, however, suggests that in the UK the CCL alone has been responsible for a more pronounced increase in energy efficiency than the CCL combined with CCAs, indicating that the energy efficiency targets

of the CCAs have provided a weaker incentive to decrease energy use compared to the price incentive of the CCL alone [115].

In spite of these policies having achieved a degree of success, a range of non-financial and financial barriers can hamper the uptake of cost-saving measures such as energy efficiency. One explanation for this put forward by economists, is that those energy efficient technologies that appear to be highly profitable must have omitted some real (but perhaps intangible) cost, else these technologies would already have been taken up ([66,116,117]). In addition, different projects must compete for capital and short-termism can often lead to production improvements being preferred over, say, energy saving improvements and deferring fouling mitigation actions [16]. Energy efficiency investments are often subject to more stringent criteria, in some cases limiting the payback time to less than 12 months [70].

For example, the UK Committee on Climate Change has identified significant cost-saving emissions abatement potential in the UK iron & steel industry (through increased use of recycled steel), cement industry (through clinker substitution), and chemicals industries (for example through less energy-intensive chemical distillation processes) by 2030 [118], but notes that long refurbishment cycles and capital constraints could hamper the uptake of these measures. It recommends that the latest CCAs, to be agreed in 2013, should include a rigorous assessment of industry abatement options with a focus on achieving longer term abatement throughout the 2020s (the CCAs will run until 2023), as well as dedicated access to capital for mitigation investments, through mechanisms such as the UK's new Green Investment Bank [119].

Outside the UK, the Greenhouse Gas Emission Reduction from Industry project in Asia and the Pacific (GERIAP) identified several barriers to the uptake of energy efficiency measures, the most important being: focus of management on production volume and turnover as opposed to production costs; lack of information on energy saving options (compounded by the absence of energy management information systems); lack of capital for even relatively short payback (e.g. two or three years) investments; and lack of clear, effectively enforced energy efficiency policies [120]. In response, Governments should enforce clear energy efficiency policies, supported by economic instruments such as fuel/emissions taxes, removal of fossil energy subsidies but provision of subsidies such as tax breaks for energy efficiency investments, improved monitoring and reporting of progress made by companies, and promotion of research and development into energy efficient technologies [121]. Governments should also, where possible, provide information on energy efficiency options for industries.

One example of such recommendations put into practice is China's 11th Five Year Plan (2006–2010) energy efficiency programmes for the industry sectors. The *Top 1000 Energy-consuming Enterprises Programme* targeted specific energy savings in the 1000 most energy-consuming firms in China (of which around half are in the iron and steel, chemicals and cement sectors) with supporting policies including energy audits, benchmarking, monitoring, information dissemination, and financial incentives [122]. The *Ten Key Energy Conservation Projects* provided Government funding for energy-intensive industries for projects such as coal-fired industrial boiler retrofits, district CHP projects, waste heat and pressure utilization projects, petroleum conservation and substitution projects, motors energy efficiency projects, and energy system optimization projects. The *Small Plant Closure Programme* targeted the closure of smaller, less energy-efficient process plants including a significant capacity of smaller vertical shaft kilns in the cement industry, and smaller blast furnaces in the steel industry [123]. In aggregate these policies have contributed to a notable reduction in the energy intensity of steel and cement, though compared to international advanced levels there remains room for further improvements (see Table 14).

Table 14
Industry product energy intensity in China.

Product energy intensity (GJ/tonne)[a]	2005 (China)	2006 (China)	Advanced level (International)
Crude steel	21.4	20.4	17.9
Cement	4.9	4.1	3.5

[a] Adapted from [123] using IEA energy conversion factors.

In addition to such programmes, a number of countries are in the process of phasing out fossil fuel subsidies, which discourage the uptake of energy efficiency measures in energy-intensive industries. For example China abolished preferential electricity tariffs for certain energy-intensive industries (including steel, cement and some chemicals sectors) in 2010, and India removed regulations on natural gas prices, more than doubling the price in 2010 [2].

In summary, a range of energy efficiency opportunities are gradually being unlocked through a variety of targeted policies. Nevertheless, as discussed in the above, further research is required in order to more completely understand the range of barriers to the uptake of seemingly cost-effective energy efficiency measures, and how to overcome these barriers.

10.3. Subsidies and carbon pricing for more expensive abatement options

Whilst the policies outlined above can drive largely cost-effective mitigation, for measures such as fuel-switching and more expensive options, some form of financial incentive (through a carbon price or subsidy) or direct regulation is needed. For example, to drive the uptake of fuel-switching away from carbon-intensive coal and gas, the UK iron and steel, cement and chemicals industries are (as of 2011) eligible for a renewable heat incentive (RHI), a Government payment for each unit of renewable heat generated, thereby subsidising the installation of technologies such as biomass and biogas combustion to produce high-grade heat (which together could meet three quarters of total industrial heat demand by 2030) [118]. Payments are intended to compensate installations for the additional cost of renewable over fossil fuel heat, for their initial capital investment in the technology, and for any non-financial barriers to the uptake of the technology [124].

Since 2005 the EU iron & steel, cement and chemicals industries have been included in the EU Emissions Trading System (EU ETS), which caps the quantities of CO_2 emissions from installations in these sectors, and allows emissions permits to be traded with other installations across the EU, establishing a common carbon price. There is evidence (both anecdotally and from statistical analysis) that industrial firms within the EU ETS have undertaken mitigation measures as a result of the policy [125]. However, the iron and steel, cement and chemicals industries have until this point had their emissions largely covered by free allowances [126]. There is some evidence that the extent to which firms in the EU ETS undertake production process and product innovations is related to their expectations of their future allocation of free allowances, rather than on expectations of the carbon price [127], which might imply that free allowances have dampened incentives to invest in emissions-reducing technologies. Free allowances have been allocated to these industries in response to concerns over the competitiveness impacts and 'carbon leakage' that could result from asymmetric climate policies (i.e. where a region imposes more stringent regulations on energy-intensive industries than other regions, thereby giving an incentive to those industries – and their emissions – to relocate abroad). A number of studies have been undertaken to assess the size of carbon leakage for

particular energy-intensive industries, with the leakage rate defined as 'the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries' [128].

Estimated leakage rates for iron and steel range from as low as 0.5% to as high as 26% [129], and cement as low as 5% [130] to as high as 70% [131,132]. Such large ranges reflect difficulties in measuring leakage empirically from historical data, due to the limited time in which the EU ETS has been operational. There is also uncertainty in estimating leakage theoretically in models of production and trade, due to the many parameters (for example abatement costs, transport costs, and market structure) that must themselves be estimated in order to do this. These factors have contributed to on-going disagreements between industry groups and the European Commission over free allocation policies. A current example concerns the methodologies used to benchmark the emissions intensity of different industry installations in each sector across the EU, with installations due to receive free allowances during the 2013–2020 period of the EU ETS based on the emissions intensity of the 10% best performers. The benchmarking methodology has led to a number of challenges, including a lawsuit from the European Confederation of Iron and Steel Industries (EUROFER) claiming that the benchmark level for hot metal is technically unachievable [133].

Free allowances based on a benchmarked emissions-intensity for the iron & steel, cement and chemicals sectors are also in use in New Zealand's ETS, which has included these industries since 2010. Nevertheless, alternative policies to tackle competitiveness and leakage concerns are under consideration, such as border adjustment mechanisms, which could place costs on imports into (or provide rebates on exports from) the EU, thereby levelising the carbon price across regions, and global sectoral agreements, which could in theory set a common emissions standard across products, regardless of where they are produced [130]. Free allowances and border adjustment mechanisms are likely to be targeted towards compensating industries for increased costs from direct emissions. In addition, competitiveness loss and carbon leakage could in theory also result from increased indirect costs, most notable through raised electricity prices as a result of low-carbon policies in the electricity sector. With this in mind, in autumn 2011 the UK's Chancellor announced in his budget statement that the UK Government would compensate key electricity-intensive businesses to help offset the increased costs of electricity resulting from carbon-pricing policies, as well as increasing the discount on the Climate Change Levy for electricity for those businesses with Climate Change Agreements [134].

As already discussed, some industry associations have already taken sector-wide initiatives towards establishing energy and emissions monitoring data for their members, thereby making more viable a move towards sectoral mechanisms. Such mechanisms could in theory take many forms, such as technology and best practice sharing agreements, or specific 'no-lose' emissions targets for whole sectors within countries or groups of countries, with the possible development of the clean development mechanism (CDM) from a project-based approach to a sector-wide approach (depending on international negotiations). The latter approach could exacerbate competitive distortions, however, as the CDM can lead to energy-intensive industrial firms in emissions-capped regions purchasing CDM credits from uncapped regions, thereby subsidising the mitigation of their international competitors [82].

11. Conclusions

Limiting industrial CO_2 emissions is crucial to reduce the risks of climate change, but this is very challenging, and more deserving of policy attention. Owing to energy intensive, fossil-fuel dependent processes and in many cases direct process emissions, CO_2 emissions from heavy industries form a large segment of global emissions. Production and associated CO_2 emissions are predicted to continue to rise, as developing countries grow and seek to improve their standards of living.

Where mitigation options have fallen in line with industry's own goals of minimising energy costs and ensuring competitiveness, progress has been made in reducing CO_2 emissions and improving energy efficiency, though many apparently cost effective efficiency measures remain unrealised. However, these actions alone will not be sufficient. Owing to its diversity and issues of international competition, industry requires special attention from policy-makers. Broad policies, grouping industry with the power and buildings sectors, are unlikely to be effective. In summary:

- There needs to be a focussed effort to improve emissions measurements and benchmarking in order to understand the full extent of energy efficiency and emissions abatement opportunities.
- All newly built plants should be at BAT and existing plants to move to BAT as quickly as possible. BAT standards should also be regularly updated on an appropriate timescale in keeping with technological advancement. Capital stock turnover is the main limitation to penetration of advanced technologies.
- Barriers to the adoption of crosscutting energy efficiency improvements should be identified and measures should be put in place to overcome them. These barriers are often 'social', such as organisational and managerial structures or lack of knowledge, rather than financial. Energy efficiency improvements are often at low or even negative cost and could make significant CO_2 savings.
- The substitution of fuels and raw materials with biomass and waste should be incentivised through appropriate mechanisms such as a carbon price, subsidies or regulations.
- Current policy efforts should also focus on the early demonstration of CCS across a broad range of industrial processes. These processes need to be ready for demonstration and commercial deployment in the early 2020s in order to sufficiently reduce emissions from these sectors over the longer term.

As has been highlighted in this paper, these key areas are likely to provide the greatest gains and should be the focus of current efforts.

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